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OVERVIEW AND PROSPECTS OF THE SuperKEKB COMMISSIONING

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Abstract

The Phase 3 beam commissioning of SuperKEKB is summarized. As for the prospects of SuperKEKB commissioning, we focus on critical issues toward the next mile stone of the luminosity of $1 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

INTRODUCTION

The purpose of SuperKEKB is to search for a new physics beyond the standard model of the particle physics in the B meson regime. SuperKEKB consists of the injector linac, a damping ring for the positron beam, two main rings; *i.e.* the low energy ring (LER) for positrons and the high energy ring (HER) for electrons and the physics detector named Belle II. The beam energies of LER and HER are 4 GeV and 7 GeV, respectively. The design beam currents of LER and HER are 3.6 A and 2.6 A, respectively. The design luminosity is $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. More detailed design parameters of SuperKEKB is described elsewhere [1]. The Phase 1 beam commissioning was done from Feb. 2016 to June 2016. In this phase, the machine operation was done without the IR (Interaction Region) devises nor the Belle II detector. The purposes of the operation in Phase 1 were vacuum scrubbing, low emittance tuning and beam background study using specially designed background detectors. The Phase 2 beam commissioning was done from March 2018 to July 2018. In this phase, a pilot run of SuperKEKB and the Belle II detector was performed. Although most of the Belle II detector was installed, the most sensitive detectors to the beam background, *i.e.* the pixel vertex detectors and the silicon vertex detectors were not installed in this phase. The purposes of the operation in Phase 2 were demonstration of "nano-beam collision scheme" and the study on beam background with much lower beta functions at the IP than those in KEKB. The achieved luminosity in Phase 2 was $5.6 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with $^{*}_{y}$ of 3 mm. The Phase 3 beam operation started in March 2019 and has continued until now. An initial report on the Phase 3 operation is shown elsewhere [2]. In this report, we summarize the progress of SuperKEKB in Phase 3. The machine operation of SuperKEKB was halted on June 22nd 2022 for a long shutdown (LS1: Long Shutdown 1). During LS1, we will do several upgrade works as is shown below. After LS1, the machine operation will be resumed in autumn 2023 or later. Also discussed in this report are critical issues on luminosity improvement after LS1. We focus on the most critical issues and more comprehensive discussions are given elsewhere [3,4].

OVERVIEW OF PHASE 3 OPERATION

The history of machine operation in Phase 3 is shown in Fig. 1. In the figure shown are the history of the HER beam current, the LER beam current, the peak luminosity and the total integrated luminosity (delivered and recorded values) from the top to the bottom, respectively. Both in the beam currents and the luminosity, there has been a great progress since IPAC2020 held in May 2020. Table 1 shows a comparison of machine parameters in 4 cases. The highest peak luminosity so far achieved is $4.65 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ as is shown in Fig. 1. This is the official record on the peak luminosity at SuperKEKB. A higher value of $4.71 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved in a test run with the Belle II detector HV off. The recorded and delivered total integrated luminosity so far are 424 and 491 fb^{-1}, respectively. In comparison between the parameters at present with those achieved by KEKB, the peak luminosity at present is more than twice higher than the achieved value at KEKB. But comparing the present beam performance with the design of SuperKEKB, we are still at an early stage of the project. In the following, we summarized progress in Phase 3 on the three parameters related to the luminosity; *i.e.* vertical beta function at the IP (β_y^*), the beam currents and the vertical beam-beam parameter (ξ_y).

Squeezing β_y^*

In Phase 2, we successfully squeezed β_y^* down to 3 mm. This value was already a half of the value achieved at KEKB and demonstrated effectiveness of the nano-beam scheme. Progress in squeezing β_y^* in Phase 3 is also shown in Fig. 1. The physics run in Phase 3 started with β_y^* of 3 mm in 2019. At the end of 2019, we successfully reached β_y^* of 1 mm. In the process of squeezing β_y^*, we found that minimising the x–y coupling parameters at the IP is essentially important to get a high luminosity. Roughly speaking, the achieved luminosity has been inversely proportional to β_y^* with the x–y coupling tuning in the range of β_y^* from 3 mm to 1 mm. In 2020 and 2022, we tried to squeeze β_y^* down to 0.8 mm as is seen in Fig. 1. The operations with β_y^* of 0.8 mm were short time trials. In both trials, we could not store the same beam currents as the case of β_y^* of 1 mm mainly due to poor injection efficiency. As a result, an achieved luminosity with β_y^* of 0.8 mm so far is much lower than that with β_y^*

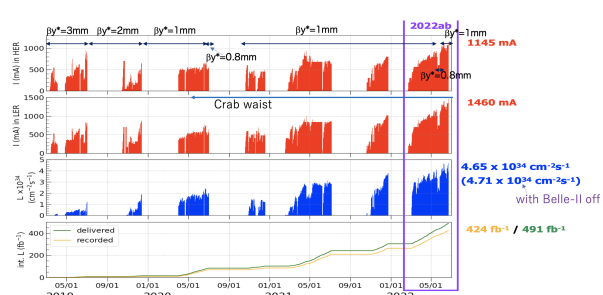

Figure 1: Operation history in Phase 3.

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Table 1: Comparison of Machine Parameters

	KEKB Achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 8th		SuperKEKB Design	
	LER	**HER**	**LER**	**HER**	**LER**	**HER**	**LER**	**HER**
I_{beam}[A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch}[mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	0.129	0.090	0.0236	0.0219	0.0407	0.0279	0.0881	0.0807
					0.0565*	0.0434*		
Luminosity [10^{34} cm^{-2}s^{-1}]	2.11		1.57		4.65		80	
Integrate luminosity [ab^{-1}]	1.04		0.03		0.41		50	

* values in high bunch current study

of 1 mm. This seems a serious problem to be solved for a higher luminosity in future. This issue is discussed in more details later in this report.

Increasing Beam Currents

Increasing the beam currents has been one of the main ways of the luminosity improvement. As shown in Fig. 1, we have been increasing beam currents gradually with fighting with several obstacles which are listed in the following.

- Hardware damages due to sudden beam losses
- Detector beam background
- Beam injection
- Beam instability

Of those obstacles, the sudden beam loss has put us the most serious restriction. As is addressed in the following section, frequent hardware troubles on collimators (and Belle II sub-detectors) happened when the bunch current in LER is larger than 0.7 mA. In comparison between the parameters at present (June 8th 2022) with those on May 1st 2020, the total beam currents increased by a factor 2 or 3. However, the increases in the bunch currents are small. The increases in the beam currents were done mainly by increasing the number of bunches. This is due to the sudden beam loss problem as is described in the next section.

Current beam background (BG) rates in Belle II are acceptable and well below limits and Belle II did not limit beam currents in 2021 and 2022. It will limit SuperKEKB beam currents eventually, without further background mitigation. To reach the design luminosity, an upgrade of crucial detector components is foreseen (e.g. short lifetime conventional PMTs for TOP (Time of Propagation) counter). The beam gas BG in LER is expected to be lowered in the process of vacuum scrubbing. We also expect that BG will be lowered by IR radiation shield reinforcement to be done in LS1. On the other hand, the luminosity related BG will increase with a higher luminosity. Issues related to beam injection are discussed in the next section.

In SuperKEKB, the apertures of vertical collimators are set very close to the beams. The half aperture of the vertical collimators is set at about 2 mm or narrower and its impedance would cause the TMCI (Transverse Mode Coupling Instability) particularly in LER. We have intensively studies their effects. We have observed vertical beam-size blow-ups around 0.8 mA/bunch in LER with single-beam operations, and this value is about 50 % or more lower than an expected TMCI threshold. When the beam-size blow-ups have been observed, a peak corresponding to $\nu_y - \nu_s$ appears and so we call this "-1 mode instability". The impedance in vertical collimators contributes to this instability and opening apertures of them can raise the threshold. The vertical bunch-by-bunch feedback system with a standard setting enhances this instability and its tunings can suppress the instability. The mechanism of the -1 mode instability has been investigated by K. Ohmi [5]. Impedance dependence of the -1 mode instability is one of motivations to introduce the nonlinear collimator. Since the apertures of vertical collimators scale as β_y^*, TMCI would set a limit on the bunch current at smaller values of β_y^*. Results of the machine study on TMCI in LER are summarized below. With the use of 2 vertical collimators and taking into account the impedance from the high-β region around final focus quadrupoles, the TMCI threshold will be lower than the design bunch current of 1.44 mA when $\beta_y^* < 0.6$ mm. By introducing a nonlinear collimator, we can raise the threshold or use more vertical collimators and meanwhile reduce Belle II BG. Coupled bunch instability from the resistive wall impedance and from the electron clouds has been well suppressed by the bunch-by-bunch feedback so far. The longitudinal coupled bunch instability caused by fundamental mode impedance of RF cavities has been well suppressed by -1 mode dampers in both rings. In the current beam condition (4 or 6 ns bunch spacing, < 0.7 mA/bunch), no significant beam size blowup due to the electron clouds effects has been observed in LER.

Beam-beam Parameters

Improving the beam-beam performance, which usually means suppression of the beam-beam blowup, is one of the most important ways to improve the luminosity. The in-

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dexes to show the beam-beam performance are the specific luminosity or the vertical beam-beam parameter. In the following, our efforts to improve the beam-beam performance in Phase 3 are summarized. The following three subjects are discussed in this report.

- Introduction of crab waist scheme
- Tuning on the IP parameters
- Tuning on the bunch-by-bunch feedback system

Crab Waist In March 2020, we decided to introduce the crab waist scheme, which was an option in the design of SuperKEKB. The motivations of the introduction were in the following. The beam-beam performance was poor in spite of all of knob tunings for improving it and it was limited by beam-beam resonances which can be suppressed by the crab waist. This is the second application of the crab waist scheme following DAΦNE [6] for actual collider machines. The crab waist scheme was realized by making an intentional imbalance of strength of paired sextupole magnets in the vertical local chromaticity correction section. The crab waist scheme was introduced by the following steps:

- 2020 March 16th : LER crab waist (40 %)
- 2020 March 24th : LER crab waist (60 %)
- 2020 April 24th : HER crab waist (40 %)
- 2020 June 1st : LER crab waist (80 %)

Here, the strength of the crab waist (crab waist ratio) is also shown. The strength (imbalance) of the crab waist sextupoles which brings the complete crab waist is 100 %. The lower crab waist ratio means the weaker crab waist sextupoles (weaker imbalance). Since the setting in the final step on June 1st 2020, the same setting of the crab waist sextupoles has been used up to now.

Effectiveness of the crab waist is shown in Fig. 2. In the figure, the green dots show the specific luminosity without the crab waist. The others show that with crab waist and the pink dots correspond to that after the final step. Here, the specific luminosity is defined as the total luminosity divided by the number of bunches and by the bunch current product. As is seen in the comparison between the green dots (w/o crab waist) and the pink dots (w/ crab waist), the specific luminosity was improved with the crab waist and the improvement is higher as the bunch currents increase. In addition, the bunch currents could be increased with the crab waist. Without the crab waist, the bunch current product was limited at around 0.38 mA^2 due to the beam-beam blowup. With the crab waist, we could increase the bunch current product up to over 0.5 mA^2. This is also a benefit of the crab waist. As a side effect of the crab waist, it was expected that dynamic aperture shrinks and the beam lifetime decreases. In the case of $^*_y$ = 1 mm, however, no lifetime decrease was observed in both LER and HER. This was because the narrow physical apertures at collimators determine the lifetime. In the case of lower $^*_y$, simulations showed the lifetime with crab waist will set a strong limit. The experimental result that the crab waist improves the specific luminosity is supported by the beam-beam simulations as is shown in Fig. 3.

While the green line in the graph shows the result of the strong-strong beam-beam simulation without the crab waist, the black line shows that with crab waist (LER:80 % and HER:40 %). In both cases, the longitudinal impedance was considered in the simulations. Effectiveness of the crab waist scheme is clearly demonstrated in the figure. Other data in the figure are experimental data taken in 2021 with the crab waist. If the simulation reproduced the experimental data correctly, the experimental data would agree with the black line. In reality, however, there is a large discrepancy.

Knob Tuning on IP Parameters Like at KEKB, tuning on beam parameters such as the local x–y coupling, the chromatic x–y coupling, the vertical dispersion at the IP are very important for increasing the luminosity. We do tuning to adjust these parameters by using skew-Q windings on sextupole magnets. As for the chromatic coupling at IP, we also use rotatable sextupole magnets installed in LER.

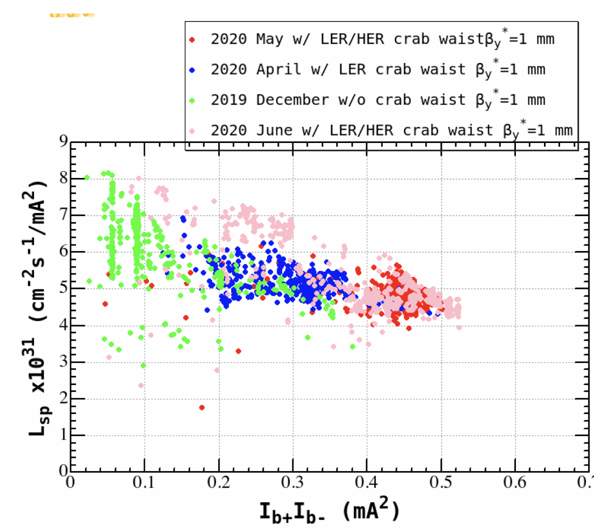

Figure 2: Comparison of specific luminosity of different crab waist settings.

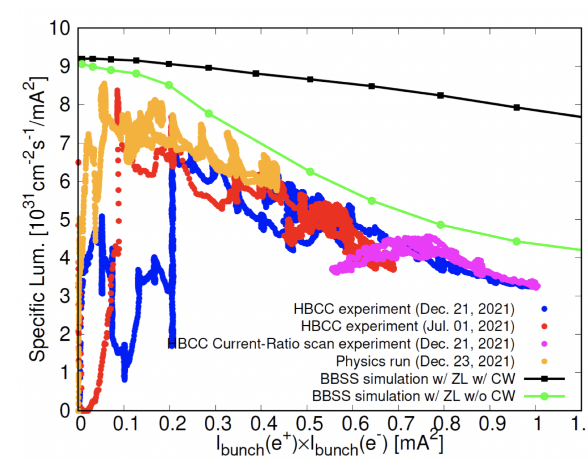

Figure 3: Beam-beam simulations without the crab waist and with the crab waist. Experimental data taken in 2021 are also shown.

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Also like at KEKB, the standard method of tuning on those parameters is to scan the parameters one by one so that the luminosity is maximized, although we also take the smaller vertical beam sizes in some cases. As is mentioned above, in the process of squeezing β_y^* from 3 mm to 1 mm, we found that minimising the x–y coupling parameters at the IP is essentially important to get a high luminosity.

Bunch-by-bunch Feedback Gain In May 2021, the luminosity increased by lowering gain of the bunch-by-bunch feedback (FB) system in HER. The FB system has two loops and the feedback gains of the both loops in the vertical direction were lowered by 4 dB. As a result of this gain change, the luminosity increased by ~ 25 %. Noise mixed in the FB system affected the luminosity. The noise was caused by a troubled module in the FB circuits. Since the noise frequency was near the betatron tune, its effect was large.

CRITICAL ISSUES AT PRESENT AND AFTER LS1 (LONG-SHUTDOWN 1)

Machine Parameters for Luminosity of $1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$

The next target of the luminosity at SuperKEKB is $1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$. We will aim at the luminosity within 1 or 2 years after LS1. In the following, examples of parameter sets with which the target luminosity would be achieved are shown. The maximum number of bunches with 2 RF bucket spacing, which is the design bucket spacing, is 2346. This number is smaller than the design value of 2500. This is because we currently use two abort gaps for faster beam abort. In the following, this number is assumed. As shown in Table 1, the achieved number of bunches is already not far from this number and we will have to increase bunch currents for a higher luminosity. The basis of the following estimation is the specific luminosity shown in Fig. 4. In the graph,

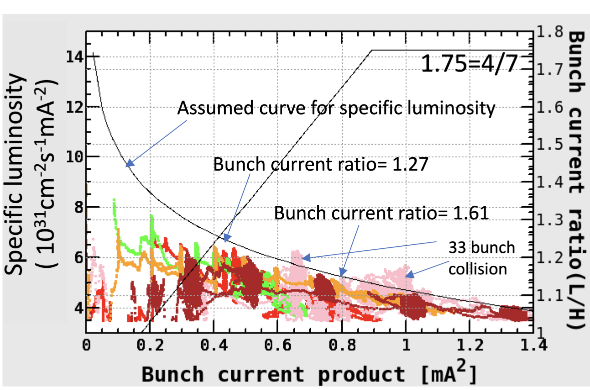

Figure 4: Specific luminosity as function of bunch current product in the case of $^*_y$ of 1mm. Assumed values of the ratio of bunch currents between LER and HER are also shown.

dots in several colors are shown. The dots in green show the specific luminosity achieved during physic experiment and dots in other colors are those achieved in high-bunch-current machine studies with fewer number of bunches. In all data, $^*_y$ was 1mm. An assumed curve for the luminosity estimation is also shown in the figure. The assumed curve of the specific luminosity is rather high compared with achieved values except for the 33 bunch collision cases. If this high specific luminosity with the smallest number of bunches (33) is reproduced in the 2346 bunches case, we could expect a higher luminosity. In the high-bunch-current machine study in 2021, the beam current ratio of LER and HER has to be increase as the function of the bunch current product as is shown in the figure. In the following, we assume that the beam current ratio increases linearly as the function of the bunch current product up to the inverse of the beam current (1.75) as is shown in the figure. With the above assumptions, the beam currents needed to achieve the luminosity of $1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$ can be estimated and are shown in Table 2. In the table, parameters in the case of $^*_y$ of 0.8 mm is also shown. In this case, the specific luminosity is assumed to be 25 % higher than the case of $^*_y$ of 1 mm. In the table, the number of bunches includes one special bunch called "pilot bunch" which is used for tune monitoring and has no collision partner bunch.

Sudden Beam Loss Events

To achieve beam parameters in Table 2, a serious obstacle is very fast beam loss events which we call as "sudden beam loss". As is shown below, those events limit the bunch current mainly in LER seriously and will be a serious obstacle to achieve the bunch currents in Table 2.

We have encountered frequently events where the beam is lost very fast and largely. The events occur in both rings but the LER beam loss is more serious. Figure 5 shows a typical data of the large beam loss event. As is seen in the figure, more than a half of the beam current was lost within 3 turns. Almost no beam oscillations were observed in both horizontal and vertical directions before the beam loss, although some vertical oscillation was observed in some other events. No beam size blowup was observed using the turn-by-turn beam size monitor before the beam loss. The large losses often cause damages of the vertical collimators and the damage brought increase of detector beam background. In some

Table 2: Parameters for Luminosity $1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$

Parameter	LER	HER	LER	HER
# of bunches	2345+1*)		2345+1*)	
Luminosity	$1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$		$1 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$	
I_{total} [A]	2.08	1.48	2.78	1.65
I_{bunch} [mA]	0.89	0.63	1.18	0.70
$^*_y$ [mm]	0.8	0.8	1	1
$^*_y$ [m]	0.154	0.154	0.211	0.211
$_z$ [mm]	6.49	6.35	7.26	6.51
Beam life-time [min.]	3.4	14.8	4.7	16.9

* including a pilot bunch w/o collision partner bunch

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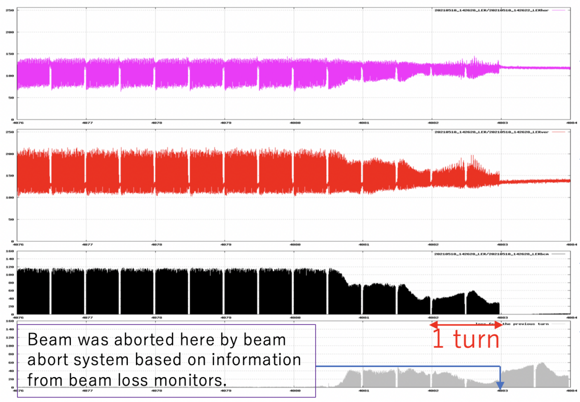

Figure 5: An observed event of an LER large and fast beam loss as function of time. The top row: horizontal oscillation from Bunch Oscillation Recorder (BOR). The second row: vertical oscillation from BOR. The third row: data of bunch current monitor (BCM). The bottom row: amount of beam loss (from BCM). The BOR amplitude is the product of oscillation amplitudes and bunch currents.

cases, the loss causes a QCS (superconducting magnets near IP) quench. In other cases, the loss causes a damage of Belle II sub-detectors. The frequency of these events has been increasing as the total beam current increases. Based on experiences of the events which occurred during the period from March to mid-May 2022, we worked out an empirical rule to prevent the events that the bunch current must not exceed 0.7 mA per bunch. The recent increase in beam currents was achieved by increasing the number of bunches while respecting this rule. It is very important to achieve the bunch currents particularly in LER shown in Table 2 to solve this serious issue.

The mechanism of the sudden beam loss has not been understood well. A hypothesis was proposed to try to explain the event in our team [7]. In the hypothesis, a microparticle heated by the beam-induced field causes a macroscopic vacuum arc and the beam is kicked by the vacuum arc. We will continue to study this hypothesis. A joint Belle II-SuperKEKB team has been working to identify the original places of the fast beam losses. Recent progress shows collimators near the injection region are the most possible candidates. Investigations are ongoing to fully understand this issue and countermeasures are being sought.

Beam Injection Issues

Currently, we conduct physics experiment with $^*_y$ of 1 mm. We tried to squeeze $^*_y$ down to 0.8 mm in June 2020 and in May 2022. The luminosity with $^*_y$ of 0.8 mm did not reach that with $^*_y$ of 1 mm both times, since the total beam currents particularly in LER was much lower than those with $^*_y$ of 1 mm due to mainly poorer injection efficiency. This means that the maximum beam currents in the rings were limited by the balance between the charge injected to the rings and the charge loss due to beam lifetime. Although he beam lifetime with $^*_y$ of 0.8 mm is somewhat shorter than that with $^*_y$ of 1 mm, the poor injection efficiency is more serious problem. The beam injection efficiency in LER as the function of the bunch currents stored in the ring is shown in Fig. 6. We observe strong beam current dependence. Here, we plot the dependence as the bunch current dependence. The reason for the beam current dependence has not been understood well. A possible reason is that the effective feedback gain for each bunch depends on the bunch current in the ring. Injection efficiency seems to be affected by beam-beam effects. We need more simulations and machine study on those issues.

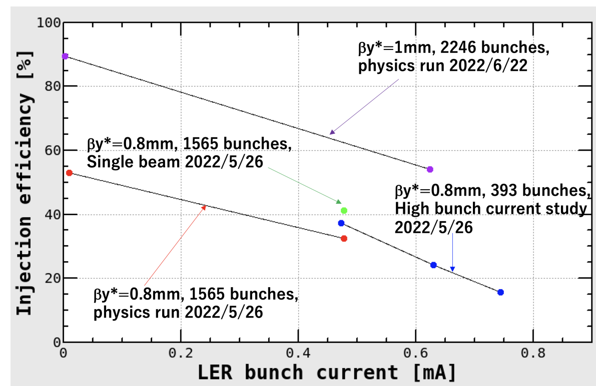

Figure 6: The injection efficiency as function of the bunch current in LER. Both cases of β_y^* of 0.8 mm and 1 mm are shown. There is strong beam current dependence. We have not yet understood the reason for the beam current dependence. Here, we plot the dependence as the bunch current dependence.

In the following, we estimate necessary injection efficiency to store the beam currents shown in Table 2. To compensate the beam loss due to beam lifetime, the following injection charge is required.

$$I_{inj,eff} \equiv I_{inj}E_{inj} = \frac{1}{f_{rev}}\frac{I_{total}}{Life}$$

Here, $I_{inj,eff}$[C/s], I_{inj}[C/s], E_{inj}, f_{rev}[Hz], I_{total}[A] and $Life$[s] denote the effective injection charge, the injection charge at the entrance of the ring, injection efficiency, the revolution frequency, the total beam current in the ring and the beam lifetime, respectively. As for the beam lifetime, the Touschek lifetime and the vacuum lifetime are considered and the luminosity lifetime from the radiative Bhabha scattering is ignored. We assume the following equations for the beam lifetimes. The Touschek beam lifetime is expressed as

$$\tau_{Touschek} = C_T \frac{n_b}{I_{total}} \sqrt{\varepsilon_x \varepsilon_y} \sigma_z.$$

Here, n_b, ε_x, ε_y and σ_z denote the number of bunches, the horizontal emittance, the vertical emittance and the bunch length, respectively. The vacuum beam lifetime is expressed as

$$\tau_{Vacuum} = C_V \frac{1}{I_{total}}.$$

In those equations, C_T and C_V are coefficients which depend on the physical and/or dynamic aperture in the rings and

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are determined experimentally. As for the vacuum beam lifetime, the effect of the Coulomb scattering is dominant and the that of Bremsstrahlung can be ignored. The ratio between the Touschek and vacuum lifetime is determined experimentally by changing the number of bunches. The Touschek liftetime is dominates over the vacuum lifetime in both rings, although the vacuum effect still plays some role in LER. In the equation of the Touschek lifetime, the data of the streak camera are used for σ_z which is dependent on the bunch currents. The value of ε_y is estimated by using the specific luminosity assumed in Fig. 4 with an assumption that the the vertical emittances of both rings are equal. As for the value of ε_x, the measured data during the physics experiment are used. With those assumptions, required injection charges as the function of the total beam currents are plotted in Figs. 7 and 8.

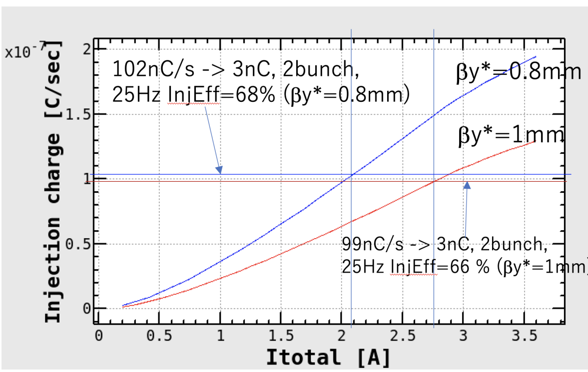

Figure 7: The required effective injection charge as the function of the total beam current in LER. The number of bunches is assumed to be 2346. Both cases of $^*_y$ = 0.8 mm and $^*_y$ = 1 mm are shown.

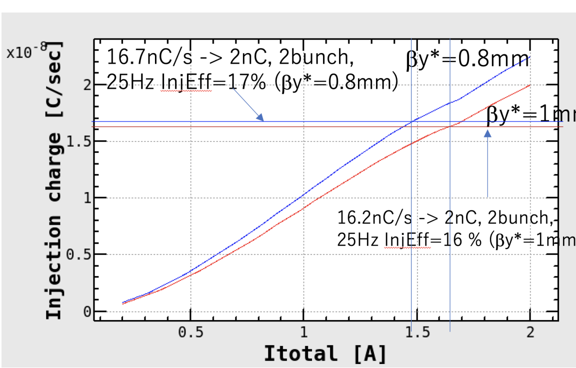

Figure 8: The required effective injection charge as the function of the total beam current in HER. The number of bunches is assumed to be 2346. Both cases of $^*_y$ = 0.8 mm and $^*_y$ = 1mm are shown.

As is seen in Fig. 7, to accumulate the beam currents of LER shown in Table 2 in the case of $^*_y$ = 0.8 mm (1 mm), we need at least the effective injection charge of 102 nC/s (99 nC/s). Those effective injection charges correspond to 3 nC injection charge at 25 Hz with 2-bunch injection and 68 % (66 %) injection efficiency. At SuperKEKB, the maximum repetition rate of the injector linac is 50 Hz which is shared by LER, HER, PF and PR-AR. The 2-bunch injection means that the 2 bunches from the injector are injected to the ring simultaneously. Due to the constraint of synchronizaiton between the injector and the rings, more number of bunches can not be injected simultaneously. In comparison between the above required injection efficiency and the achieved values shown in Fig. 6, we need improvement in the injection efficiency. Particularly in the case of $^*_y$ = 0.8 mm, we need drastic improvement such as drastic improvement in the dynamic aperture. It is important to solve the problem of the strong bunch current dependence of the injection efficiency. As for the injection charge, 3 nC per bunch has been already achieved. Since the design value of the positron charge is 4 nC per bunch, there is some room for improvement. Improvement in the beam lifetime is also helpful. As is seen in Fig. 8, to accumulate the beam currents of HER shown in Table 2 in the case of $^*_y$ = 0.8 mm (1 mm), we need at least the effective injection charge of 16.7nC/s (16.2 nC/s). Those effective injection charges correspond to 2 nC injection charge at 25Hz with 2-bunch injection and 17 % (16 %) injection efficiency. In the actual operation, the injection charge of 1.5 nC per bunch is achieved. The beam injection with the injection charge of 2 nC per bunch and the 2-bunch injection will be possible with some efforts. The design injection charge of HER is also 4 nC. With consideration of achieved injection efficiency, a typical value of which in the physics run is 50% in both $^*_y$ = 0.8 mm and 1 mm, we can be rather optimistic in the HER injection. As for the repetition rate, those of PF and PF-AR are less than 1 Hz in the top-up injection. If we can reduce the repetition rate of HER down to less than 25 Hz, we may increase the injection rate of LER from 25 Hz to some extent to mitigate difficulty of the LER injection.

WORKS IN LS1 AND BEAM OPERATION AFTER LS1

SuperKEKB will be shut down from July 2022 to September 2023. We call this shutdown as Long-Shutdown 1 (LS1). The main purpose of LS1 is to install additional VXD's (vertex detectors) and to replace a vulnerable part of PMTs of the TOP counters. In this opportunity, the following works will also be done on the accelerator side.

- IR radiation shield reinforcement for BG reduction
- Installation of a nonlinear collimator for impedance and BG reduction
- Replace collimator heads with robust ones in LER
- New beam pipes with wider aperture at HER injection point for improvement of injection efficiency
- others

Within 1 or 2 years after LS1, we will aim at the luminosity of 1×10^{35} $cm^{-2}s^{-1}$ with $\beta^*_y = 0.8$ mm. We will also try to squeeze β^*_y down to 0.6 mm.

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