THE SUPERKEKB HAS BROKEN THE WORLD RECORD OF THE LUMINOSITY

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Abstract

The SuperKEKB broke the world record of the luminosity in June 2020 in the Phase 3 operation. The luminosity has been increasing since then and the present highest luminosity is $4.65 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with β_y^* of 1 mm. The increase of the luminosity was brought with an application of crab waist, by increasing beam currents and by other improvements in the specific luminosity. In this paper, we describe what we have achieved and what we are struggling with. Finally, we mention a future plan briefly.

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 parameters of SuperKEKB is described elsewhere [1]. 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 after IPAC2020.

OPERATION HISTORY

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. In comparison between the parameters at present (June 8th 2022) with those on May 1st 2020, the peak luminosity has increased about by a factor 3. This increase of the luminosity has been mainly brought by the increase in the beam currents and the improvement in the specific luminosity. In both cases β_y^* is the same value, 1 mm. With the similar bunch currents, the vertical beam-beam parameters have been improved. This indicates that the specific luminosity has been improved. 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 if we compare the present beam performance with the design values of SuperKEKB, we are still at an early stage of the project.

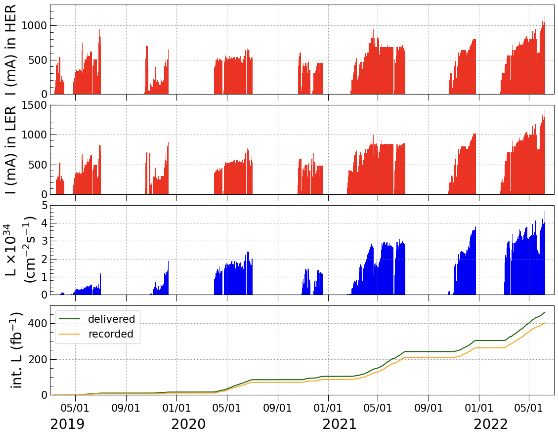

Figure 1: Operation history in Phase 3.

A comparison of the peak luminosity of various colliders as the function of the CMS (center-of-mass system) energy is shown in Fig. 2. On June 17th 2009, KEKB set an luminosity record of $2.11 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This record was bettered by LHC in May 2018. On June 15th 2020, the luminosity of SuperKEKB broke the world records which had been set by LHC. The highest luminosity accomplished by SuperKEKB on June 8th 2022 is $4.65 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

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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 0.0565*	0.0279 0.0434*	0.0881	0.0807
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

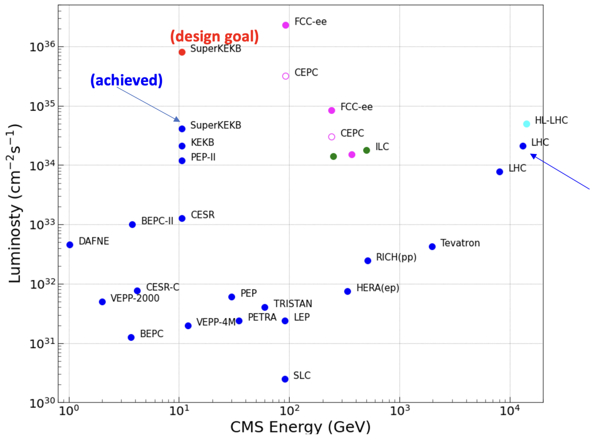

Figure 2: Comparison of luminosity of various machines.

LUMINOSITY IMPROVEMENT

Crab waist scheme

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 [3] for actual collider machines. The crab waist scheme was realized by making an intentional imbalance of strength of sextupole magnets in the vertical local chromaticity correction section. The crab waist scheme was introduced by following the steps described blow.

- 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. 3. 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 0.38mA^2 due to the beam-beam blowup. With the crab waist, we could increase the bunch current product up to over 0.5mA^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 lifetime decreases. In the case of $\beta_y^* = 1$mm, however, no lifetime decrease was observed in both LER and HER. This was because the narrow physical apertures at collimators

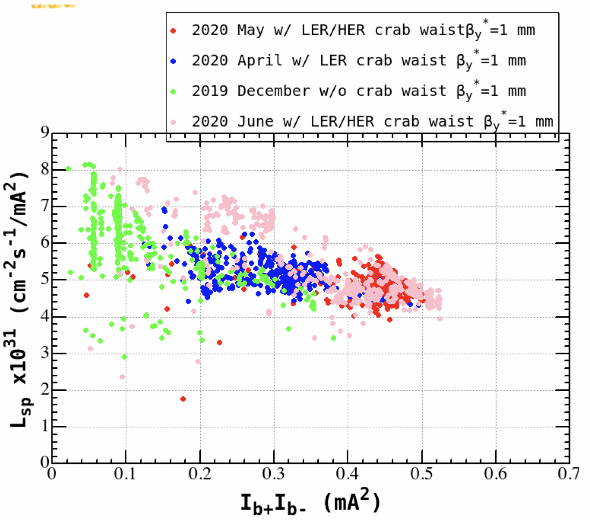

Figure 3: Comparison of specific luminosity of different crab waist settings.

determine the lifetime. In the case of lower β_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. 4. 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. As for this disagreement, we will mention again in the following section.

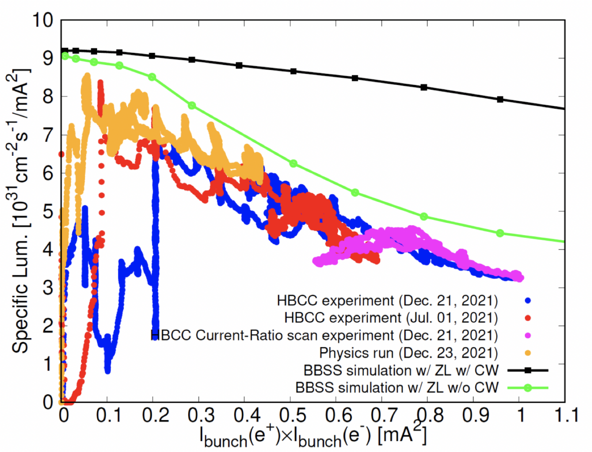

Figure 4: Beam-beam simulations without the crab waist and with the crab waist. Experimental data taken in 2021 are also shown.

Increasing beam currents

Increasing the beam currents has been one of the main causes 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 fast and large beam losses
- Detector beam background
- Beam injection
- Beam aborts
- Beam instability

Of those obstacles, the fast and large 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. The recent increase in beam currents was achieved by increasing the number of bunches while respecting the limit from bunch current limit (< 0.7mA/bunch). 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. On the other hand, the luminosity related BG will increase with a higher luminosity.

Bunch-by-bunch feedback gain

In May 2021, the luminosity increased by lowering gain of the bunch-by-bunch feedback system in HER. The feedback system has two loops and the feedback gains of the both loops in the vertical direction were lowered by 4dB. 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. Since the noise frequency was near the betatron tune, its effect was large.

Squeezing β_y^*

Figure 5 shows a history of β_y^* in various machines. Also as for squeezing β_y^*, SuperKEKB is the front runner in the world. In usual physics run, the machine is operated with β_y^* of 1 mm. In 2020 and 2022, we tried to squeeze β_y^* down to 0.8mm. Figure 6 shows the specific luminosity achieved in 2021 and 2022 as function of the bunch current product. The orange dots show the specific luminosity with β_y^* of 0.8 mm and others are data with β_y^* of 1mm. The specific luminosity with β_y^* of 0.8 mm was higher than those with β_y^* of 1 mm. The operation with β_y^* of 0.8 mm was a short time trial and we could not store higher bunch currents due to poor injection efficiency. We will retry it again and expect a higher luminosity than that with β_y^* of 1 mm in near future with improving the injection efficiency. In the data in cyan and blue, estimated values of β_y^* in HER were less than 1 mm, 0.8 mm or lower, with the setting value of β_y^* of 1 mm due to horizontal orbit change in SLY's depending on the total beam current. Here, SLY means the sextupoles for the vertical local chromaticity corrections near IP (Interaction Point). We achieved an unexpectedly higher luminosity with this unexpectedly low β_y^*.

PERFORMANCE LIMITING ISSUES

Fast and large beam loss

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 7 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

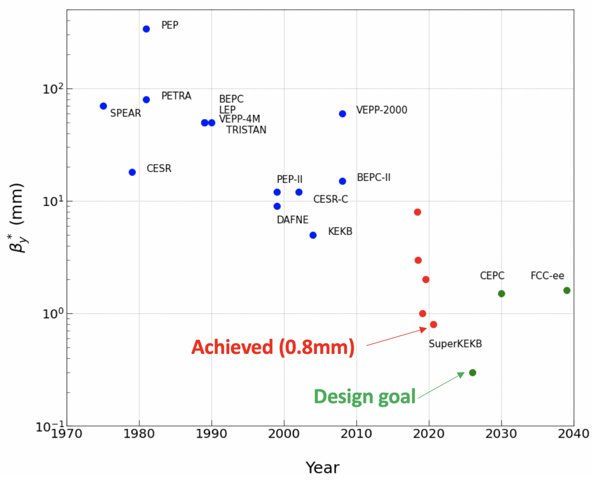

Figure 5: History of the IP vertical beta function (β_y^*) in various machines.

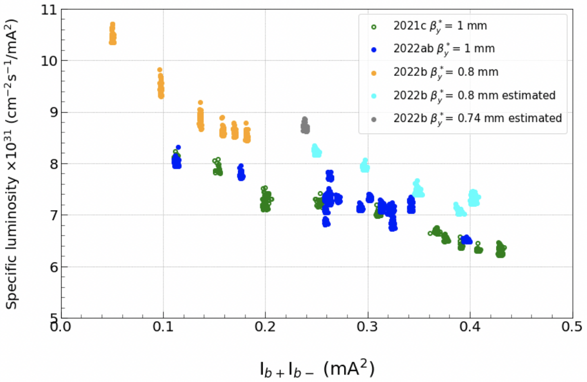

Figure 6: Specific luminosity achieved in 2021 and 2022 as function of the bunch current product.

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. We have been very conservative in increasing beam currents, particularly bunch currents. This issue limits the speed of increasing beam currents and then slows down increase of luminosity. The mechanism of the fast beam loss has not been understood well. A hypothesis was proposed to try to explain the event in our team. 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 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.

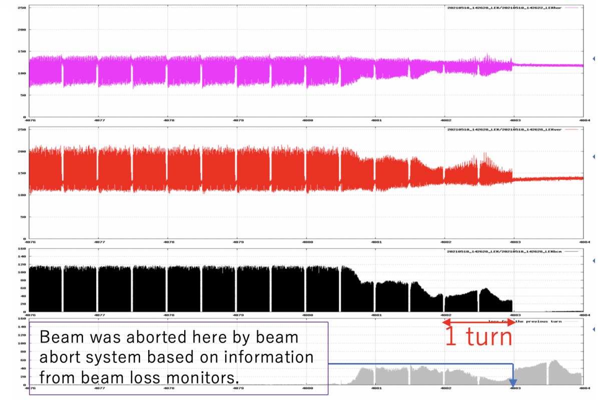

Figure 7: An observed event of an LER large and fast beam loss as function of time. The top row: horizontal oscillation from Bunch Oscillation Recorder (BOR). The second row: vertical oscillation from BOR. The third row: data of bunch current monitor (BCM). The bottom row: amount of beam loss (from BCM). The BOR amplitude is the product of oscillation amplitudes and bunch currents.

Beam injection

We summarize the SuperKEKB injection scheme below. The injector Linac provides the e+ and e- beams (e+: thermionic gun, e-: RF gun). The DR is used for the e+ beam. Synchronization between the injector and the rings allows 1-bunch or 2-bunch injection per pulse.Top-up injection is achieved for e+ and e- beams at 50 Hz at maximum (sum of e- and e+). We will face a serious problem that the maximum beam currents in the rings are determined by the balance between the charge sent from Linac and the charge loss due to beam lifetime. The shorter beam lifetime at smaller β_y^* due to the decrease of dynamic aperture requires a more powerful injection. Conversely, injection sets a limit on the achievable β_y^*. This issue will become more serious in future with smaller β_y^*. However, even now with $\beta_y^* = 1$ mm, the beam currents are limited by the beam injection sometimes when the injection efficiency becomes low. Typical values of injection efficiency with $\beta_y^* = 1$ mm are 50 % and 40 % for LER and HER, respectively and it changes largely depending on machine conditions and tuning. The injection efficiency depends on various parameters; machine tuning conditions, collimator setting, bunch currents, β_y^* and so on. Improving the injection efficiency will be an importance subject hereafter. One of the important issues on the injection efficiency is emittance preservation in Linac and the beam transport (BT) lines. The design values of normalized emittance of the e- beam are 40 and 20μm, in the horizontal and vertical directions, respectively. They are 100 and 15μm, for the e+ beam. From Linac to the beginning of BT, the design emittances are almost realised. However, at the end of BT, the emittances get larger by a factor of 3 or 5 in both beams and in the both directions. The emittance growth depends on the bunch charge. The effect of CSR (Coherent Synchrotron Radiation) is suspected as the cause. We need to study further and to find countermeasures. In future, we also need to increase the charge of the Linac beam. The achieved values of the charge of the e- and e+ beams at the end of BT are 1.5 nC and 3 nC per bunch, respectively as a result of continuous efforts. The design values are 4 nC per bunch for both beams.

Beam-beam performance

As shown in Fig. 4, observed luminosity performance is much lower than simulations. This has been and will be a challenge at SuperKEKB. Candidates of causes of the discrepancy are machine imperfections such as non-zero linear and chromatic coupling and dispersions at IP, beam-current dependent optics distortion due to orbit change at QCS and SLY's and so on. Imperfect crab waist scheme and interplay of beam-beam interaction and beam coupling impedance could be the causes. The recent observation that luminosity degrades by $\sim 4\%$ during LER injection can explain a part of the discrepancy. For improving beam-beam performance, beam-beam simulations predict better performance with smaller vertical emittance in the single beam, which is a challenge of optics corrections, and a higher crab waist ratio in HER. Other possibilities are identification of causes of the discrepancy between the simulations and the experiments and finding better working points. As for the beam-beam parameters, achieved values of ξ_y's in physics runs are 0.0392 and 0.0269 in LER and HER, respectively. Achieved values in high bunch current collision study are 0.0565 and 0.0434. By increasing bunch currents in physics run, higher ξ_y's and then a higher luminosity are expected.

Impedance related issues

In SuperKEKB, the apertures of vertical collimators are set very close to the beams. The half aperture of the vertical collimators is set 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 increase 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 is still under investigation, but we have found two ways to deal with this instability; (1) Tuning of the vertical bunch-by-bunch feedback, (2) Reducing the impedance in the vertical direction by opening vertical collimators. The second point is one of motivations to introduce the nonlinear collimator. The apertures of vertical collimators scale as β_y^*, TMCI will set a limit on the bunch current. 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.

FUTURE PLANS

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 $1 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with $\beta_y^* = 0.8$ mm. We will also try to squeeze β_y^* down to 0.6 mm.

To squeeze β_y^* down to design values (0.27 mm in LER and 0.30 mm in HER), further upgrade works will be required, including an extensive IR upgrade to improve beam lifetime. We have a plan to do those upgrade works in Long-Shutdown 2 (LS2) in around 2027. The upgrade plan is being studied. The international task force for SuperKEKB upgrade has been organized and in action since July 2021. On important issues at SuperKEKB, the SuperKEKB team is working together with the task force in four working groups; optics, beam-beam, TMCI and injector Linac. The mission of the task force is to bring ideas and exchange notes to solve various problems at SuperKEKB as a luminosity frontier machine, to achieve SuperKEKB design luminosity.

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