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STATUS OF SuperKEKB AND EXPERIENCE WITH NONLINEAR COLLIMATION

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Abstract

The SuperKEKB accelerator has resumed operation after a first long shutdown (LS1) of more than a year. During the LS1, many improvements such as the replacement of the damaged collimator heads, improvement of radiation shields to the Belle II detector has been made. In addition, a nonlinear collimator has been installed at OHO straight section of the low energy ring. Current operation status, experience with nonlinear collimator and the challenges to increase beam currents as well as luminosity are shown.

INTRODUCTION

SuperKEKB is a positron-electron collider with a nano-beam scheme, which currently achieves the world's highest luminosity for the production of B meson pairs. It consists of a 4 GeV positron ring (LER) and 7 GeV electron ring (HER). The collision to get the physics data was started in March 2018 with a test run to confirm a nano-beam scheme (Phase 2 operation), and then the physics run (Phase 3 operation) with almost full function of Belle II detector began in March 2019. The vertical betatron function at the IP, β^*y was squeezed down to 1 mm (also 0.8 mm operation was tried around 2 weeks). The crab waist (CW) scheme was adopted for both rings since the 2020b run. The CW ratio is 80% in the LER and 40% in the HER, respectively. Before the LS1, a peak luminosity of $4.65 \times 10^{34} cm^{-2} s^{-1}$ has been achieved. The machine parameters that accomplished the peak luminosity are presented in Table 1.

Table 1: Machine Parameters Achieved at SuperKEKB

Parameters	LER		HER
I (A)	1.321		1.099
n_b		2249	
I_b (mA)	0.587		0.489
β^*_x (mm)	80		60
β^*y (mm)	1.0		1.0
ξ_y	0.0407		0.0279
ε_y (pm)	31.7		31.7
σ_z (mm)	5.69		6.02
CW ratio (%)	80		40
L ($cm^{-2}s^{-1}$)		4.65×10^{34}	

After the 2022b run, we have entered the long shutdown 1 to upgrade the Belle II detector and machine. Various upgrades have been performed during this period. The commissioning of the rings has restarted on January 29th of 2024. In parallel with the vacuum scrubbing runs using beams with largely detuned optics at interaction region (IR), detailed machine studies to understand and to increase the performance for the rings have been conducted. After the scrubbing the rings, the βy^* has been shrunk step by step, from 8 mm to 3 mm, and finally down to 1 mm. The effect of the crab waist has also been examined with the optics of βy^*=1 mm and confirmed the necessity of the crab waist with the larger bunch current region.

The performance of the newly installed nonlinear collimator (NLC) has also been studied. By narrowing the collimator gap, the reduction of the beam background of stored beam has been confirmed, almost as expected. On the other hand, the suppression of beam background coming from the injection beam was not so effective, which could be explained as the cancellation of the skew sextupole kick due to large horizontal orbit of the injection beam.

First, we will give an overview of the accelerator performance improvement works carried out during LS1. Next, several results found with the accelerator studies during commissioning after LS1, including the performance of NLC. Finally, current operation status and challenges encountered during operation are shown.

ACCELERATOR WORKS DURING LS1

Figure 1 shows the vacuum-work places vented during LS1 in red lines. In addition to this, half of the positron damping ring, and several parts of the beam transport lines have been released with a dry nitrogen. Most of the damaged collimator heads have been replaced with the now ones. Figure 2 shows the places and the names of the collimator in the SuperKEKB rings. In LER, new copper-coated Titanium heads (D06V1, vertical), copper-coated Tantalum heads (D02V1 Ta :10 mm, D05V1 Ta : 4mm, vertical) and copper-coated carbon heads (D06H3, horizontal) have been installed. The new D06V1 and D06V2 vertical collimators are expected to work as the radiator (D06V1) and stopper (D06V2) for the crazy beam to protect other important collimators such as D02V1. The D06H3 horizontal collimator with carbon heads are expected to withstand instant huge beam losses coming from the accidental firing of the injection kicker. The copper-coating of the heads is expected to reduce the transverse beam-coupling impedance.

In LER, several collimators have been relocated (D06H1 to D06H4, D03V1 to D05V1) to improve the beam-cut efficiency. More than one set of spear jaws of the collimators were manufactured to prepare for future failures. Several stepping motor controllers and the position read-back of old KEKB-type collimator in HER have been renewed to improve tunability of the collimators.

The vacuum leak found in the right side of the final focusing superconducting magnet (QCS-R) cryostat has been

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investigated and repaired. To increase the injection efficiency of the HER, new vacuum chamber and the final septum magnet with increased physical aperture has been installed. The radiation shields around the IR have been added to further suppress the radiation dose to the Belle II detector.

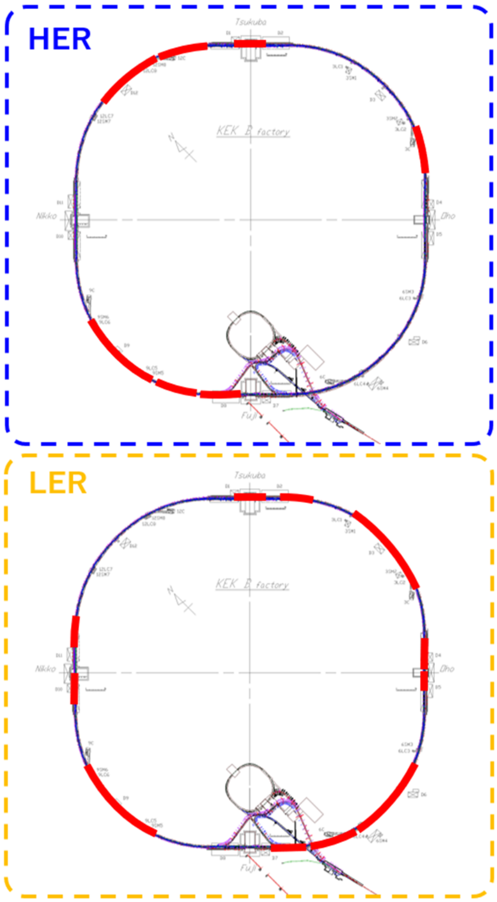

Figure 1: Vacuum-work places of SuperKEKB MR in red line during LS1.

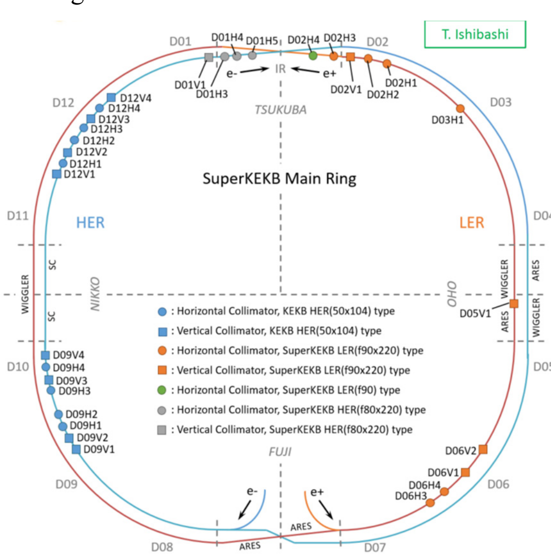

Figure 2: Location of beam collimators in SuperKEKB rings.

The world's first nonlinear collimator system (NLC) has been successfully installed in OHO straight section in the LER. Fifty damping wiggler magnets are removed and a set of newly fabricated skew sextupole magnets are installed as shown in Fig. 3. Power supplies corresponding

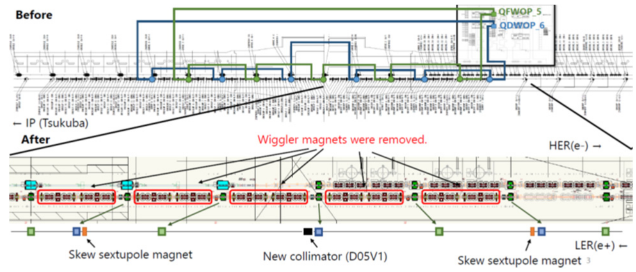

Figure 3: Nonlinear collimator system (NLC) installed at OHO straight section of LER.

for these modifications as well as the power cables to the magnets have been installed and tuned. Due to recent delays of electrical components after COVID-19, it became clear that some power supplies would not be delivered by the time operations resumed, so backup power supplies were readjusted and used. The late-delivered power supplies were by the end of March, so it is scheduled to be replaced during the maintenance time this summer.

The radiation shield near the IR has been enforced by adding the heavy metal shield around the bellows to connect IP beam pipe and QCS vacuum chamber. The concrete shields around the QCS magnets are also modified to stop the neutrons from the upstream of the beam to protect Belle II detector.

Suppressing the sudden beam loss (SBL) [1], the event where some part of bunch train was lost within one or two turns without significant bunch oscillation, is one of the crucial keys to increase luminosity. More monitors such as fast beam loss monitors and acoustic sensors [2] to get the sound of discharge in the vacuum chamber with fine timing information using White Rabbit technology [3] are being installed around the collimators and vacuum chambers near QCS collaborating with the Belle II group. The acoustic sensors are expected to capture the sound coming from the discharge phenomenon inside the vacuum chamber, which is thought to be a likely cause of SBL, and observe the fine timing compared to the beam abort timing. The post-mortem bunch position monitor to record the individual bunch oscillation just before the beam abort (BOR) have been enforced by adding existing bunch feedback processors (iGp12), simplified BOR with oscilloscope or RFSoC evaluation board with 12-bit 4 GSPS sampling rate (synchronized to 8 times of f_{RF}) [4].

In the injector electron-positron Linac, 16 old acceleration structures have been replaced by new ones with larger energy gain. New fast kickers which enable kicking the first and second bunch with the separation of 96 ns independently, larger aperture pulsed quadrupole magnets have been installed and tested. Also, installation of new energy compression section (ECS) for 7 GeV electron beam are under preparation and will be installed in summer shutdown of 2024.

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Aging countermeasures and improvements of energy efficiency for some components are taken, replacements of old and damaged components are also being done.

OPERATION STATUS AFTER LS1

Operation Overview

The commissioning of the rings has restarted on January 29th of 2024. In parallel with the vacuum scrubbing runs using beams with largely detuned optics at IR, detailed machine studies to understand and increase the performance of the rings have been conducted. After the scrubbing the rings around 100 Ah, the βy* has been shrunk step by step, from 8 mm to 3 mm, and finally 1 mm. The effect of the crab waist has also been examined with the optics of βy*= 1 mm and confirmed the necessity of the crab waist with the larger bunch current region. The number of bunches has been almost fixed with 2346 with most bunch spacing of 4 ns while the total beam current has been gradually increased. Figure 4 shows the beam current (top), peak luminosity (second), recorded and delivered luminosity (third) and integrated luminosity (bottom).

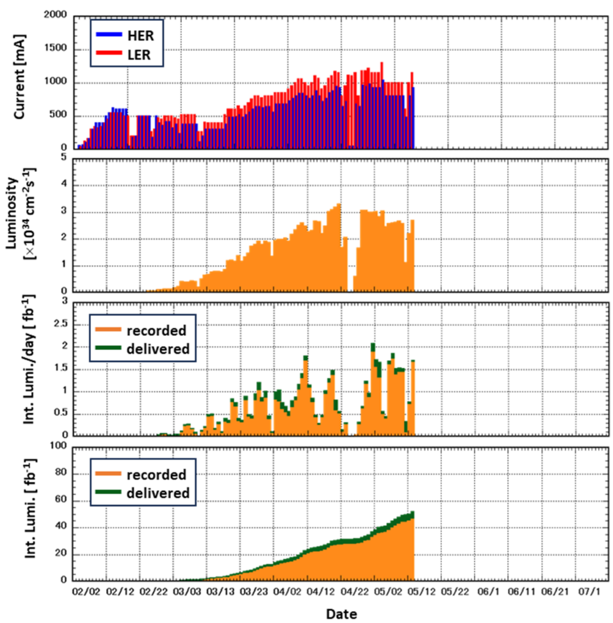

Figure 4: Operation history from the restart after LS1 : beam current (top), peak and daily luminosity (2nd and 3rd), integrated luminosity (bottom).

Performance of Nonlinear Collimator

The nonlinear collimator system consists of a pair of skew sextupole magnets (SNAP1 and SNAP2) with the betatron phase advance of 180 degrees which satisfies the *I'* relationship, and a vertical collimator. The conceptual diagram is shown in Fig. 5. The first skew sextupole magnet kicks halo components of the beam as $\frac{K_s}{2}(y^2 - x^2)$, where *y* and *x* are the vertical and horizontal orbit distortion at the skew sextupole. As the K_s is proportional to the product of the vertical betatron function at the skew sextupole and the strength of the skew sextupole, it is needed to modify the optics to have very large vertical betatron function at the skew sextupole. On the other hand, large vertical betatron function is not needed at the collimator position which greatly contributes to reduce the beam coupling impedance.

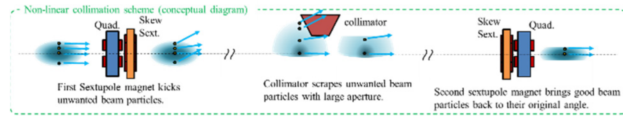

Figure 5: Conceptual diagram of nonlinear collimation scheme.

After the beam halo components have been scraped by the vertical collimator, the second skew sextupole brings the good beam particles back to their original angle due to *I'* relationship between the pair of skew sextupoles. Figure 6 shows the beam optics before and after the installation of NLC system at OHO straight section.

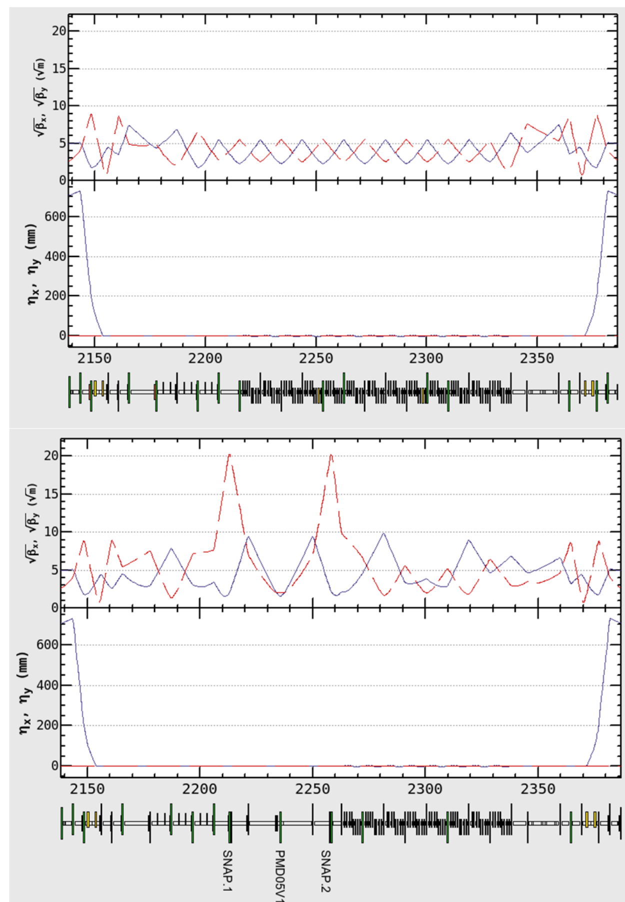

Figure 6: LER beam optics around the NLC. Upper and lower figure show the optics before and after the installation of NLC, respectively.

We have started the beam commissioning almost zero-current of SNAP1/2 and without large βy at the skew sextupoles. After establishing the orbit of LER, we have changed the optics to large βy at skew and gradually increased the excitation of skew sextupole up to the design current and realized that the stabilization of the beam orbit at the skew sextupole magnet is very important to keep the betatron tune. The local orbit correction scheme has been

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implemented in the closed-orbit control and the drift of the tune has been suppressed successfully.

The performance of NLC (D05V1 collimator) has been examined with several point of view. Before the LS1, we have mainly used the vertical collimators of D06V1 to reduce the beam background and to protect the D02V1 vertical collimator which is the nearest vertical collimator to Belle II detector.

The beam lifetime and beam injection efficiency after the introduction of NLC do not seem to change at this stage of βy^*=1 mm. The reduction of the transverse beam impedance of collimators has been confirmed by measuring the single-bunch transverse tune shift with bunch current. The reduction of beam lifetime with closing the D05V1 collimator has been compared with the case of D06V1 collimator with the effective same collimation gap as shown in Fig. 7. The measured lifetime was almost the same as expected.

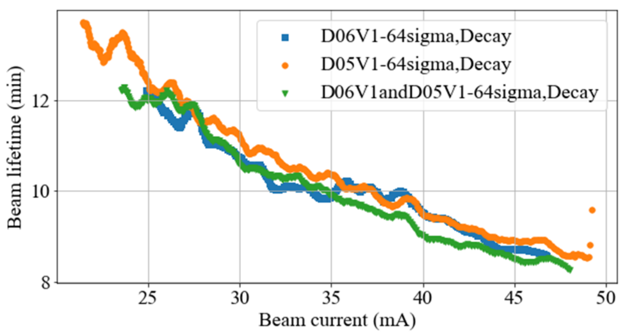

Figure 7: Measured beam lifetime with the effective collimator gap of 64 sigma of the vertical beam size for the D06V1 only, D05V1 only and D06V1 and D05V1 cases.

The beam background of stored beam to the Belle II detector was also measured with the similar condition as shown in Fig. 8. Clearly, with the same effective collimator gap, NLC scraped more beam hallo.

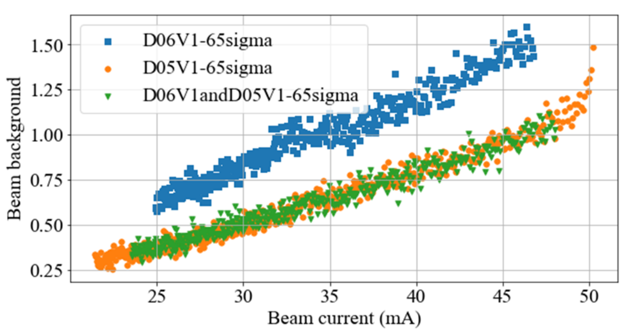

Figure 8: The beam background to the Belle II detector with the same effective vertical gap of the beam collimators. Clearly D05V1 (NLC) works better to reduce the beam background.

On the other hand, the measured reduction of the background coming from injection beam was less than that of D06V1. It might be explained as the consequence of much larger horizontal orbit of injected bunch at the skew sextupole magnet which reduced the nonlinear kick. If so, it could be improved by lowering the βx at the skew sextupole from 7 m (operating now) down to 2 m. This modification will be studied by the end of this 2024b run.

Another large challenge with the NLC system is that the radiation level in the OHO Experimental Hall building increases as closing the D05V1 gap. Although the current radiation level is not high enough to be a problem in terms of laws, countermeasures are necessary considering the future increase in beam current. We have measured the space distribution of the radiation in the building and made the simulation on the effect of the extra radiation shield to be added. During the summer maintenance time of this year, we will add the significant radiation shield around the vacuum chamber and the beam collimator.

CHALLENGES ENCOUNTERD IN THE OPERATION AFTER LS1

As increasing the total beam current of LER, the SBL phenomenon begins to occur, which is hinderring stable operaton. Befoer LS1, the SBL phenomenon were thougth to have the following characteristics :

- Significant charges of a part to bunch train have lost within one turn. Before the beam loss, no large oscillations of the bunch have been observed.
- Happened in both HER and LER, with similar rate.
- Especially in LER, it seemed that there existed a threshold in bunch current, around 0.65 mA/bunch.
- In LER, SBL damaged the vertical collimator heads, especially D06V1 and D02V1 and quenched the superconducting coils of QCS. After significant damage of the collimator heads, the threshold of SBL has been reduced.

As a countermeasure for SBL, we have performed as much work as possible during LS1. The damaged collimator heads including horizontal ones have been replaced with the new ones with stronger (carbon or titanium with copper-coated) structures. New fast beam loss monitors have been installed near the collimators to abort crazy beam as fast as possible. Acoustic sensors have been installed at the several vertical collimators to observe the discharge like sound in the collimator. The bunch oscillation recorder to record the post-mortem behaviour of the bunches just before the beam abort have been strengthened with the addition of iGp12 BRAM information and the simplified BOR using RFSoCs or oscilloscopes. As the two BPMs for the bunch feedback system has the betatron phase advance of 90 degrees in both plane in LER, it could contribute to analyse the position information of the first kick of the oscillation for SBL.

After LS1, the situation has changed as:

- Happened mainly in LER, starting with much lower bunch current than before LS1, around 0.3 mA/bunch.
- Small oscillation (less than 0.4 mm at the bunch feedback monitor) has been observed before 1 or 2 turns of the beam loss.
- It seems that the rate of SBL reduces with the integrated beam dose.
- SBL occurred with the non-collision condition.

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Figure 9 shows an example of SBL event which occurred the total beam current of 1146 mA, 0.49 mA/bunch in LER. Just one turn before the beam loss, horizontal oscillations along the bunch train has been observed at the downstream monitor. No significant vertical oscillations have been observed before the beam loss in this case. The first beam loss is often detected with D05V1 (NLC), but in this case, the first loss was detected at the injection point, and the loss was sequentially detected by the downstream loss monitors.

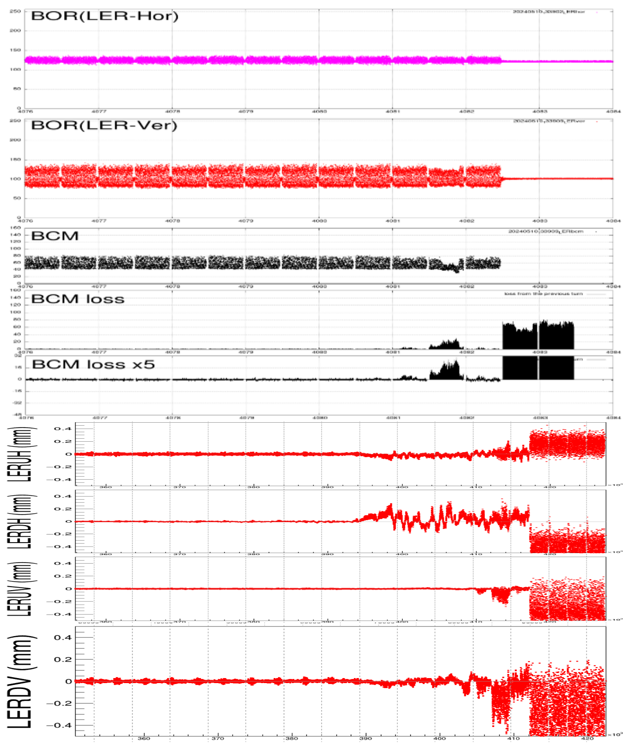

Figure 9: An example of the SBL at LER. Upper figure shows the BOR (H and V, both use the upstream BPM on the bunch feedback system), bunch current information, the loss per turn in bunch current. Lower figures show the reconstructed bunch by bunch position data from bunch feedback processors.

Up to now, only D02V1 collimator heads have tiny scratches due to large beam loss with QCS quench. Significant worsening of either beam background to the Belle II detector nor beam tune shift due to the transverse impedance has not observed with this damage. Nevertheless, one SBL event with QCS quench caused the significant damage to the Pixel detector system at the innermost part of the Belle II detector. The clear understanding of the SBL mechanism and its suppression, or at least establishment a much safer method to protect Belle II detector, is an urgently required.

SUMMARY

The SuperKEKB accelerator has resumed operation after a long shutdown 1 of more than a year. During the LS1, many improvements such as the replacement of the damaged collimator heads, countermeasures to the sudden beam loss events, improvement of radiation shields to the Belle II detector has been made. In addition, a nonlinear collimator has been installed at OHO straight section of the low energy ring. The performance of the newly installed NLC was as expected, more radiation shields will be needed for future high current operation, though.

Though the collider has almost resumed the performance before LS1, many sudden beam loss events hinder the increase of peak and integrated luminosity and stable operation. We are now working hard on research to elucidate and suppress the SBL mechanism.

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