PROCEEDINGS OF SCIENCE

Highlight from SuperKEKB Beam Commissioning after Upgrading during Long Shutdown 1

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The SuperKEKB is a high-luminosity electron–positron collider where the "nanobeam collision scheme" is utilized to achieve an unprecedented high luminosity. While its luminosity performance had gradually improved, it had been found that the SuperKEKB encountered some challenges as a luminosity frontier machine, such as severe beam instabilities—including sudden beam loss (SBL), low injection efficiency, and low machine stability. To overcome these challenges, we enforced a long shutdown (LS1) from July 2022 to January 2024 to perform numerous upgrades, including the construction of a nonlinear collimation (NLC) system and modification of the injection point. The first commissioning after the LS1 was conducted from January to July 2024. Even though the SBL was the major issue, several new findings emerged from the commissioning. Based on these, it was suggested that dust may cause the SBL. The injection efficiency was considerably improved during the last 2 weeks of the commissioning. To our knowledge, the effectiveness of the NLC for the strange beam background noise of the physics detector was demonstrated for the first time. The peak luminosity was 4.47×10^{34} cm^{-2}s^{-1} with a vertical beta function at the interaction point of 0.9 mm, and the integrated luminosity during this run was 103 fb^{-1}.

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1. Introduction

The SuperKEKB [1] is an asymmetric-energy electron–positron collider operating at KEK in search of new physics principles in the B-meson regime. It is an accelerator complex consisting of an injector (Linac), a positron damping ring, beam transport lines (BT), and a main ring (MR) with the Belle II particle detector. The MR is composed of a 4 GeV positron ring (low-energy ring (LER)) and a 7 GeV electron ring (high-energy ring (HER)), each with a circumference of 3016 m. In the SuperKEKB, the vertical beta function at the interaction point (β_y^*) can be squeezed considerably more than the bunch length without luminosity degradation owing to the hourglass effect by crossing the beam using the "nanobeam scheme" [2].

The physics run (Phase-3 operation) started in March 2019 after a test run to confirm the nano-beam scheme (Phase-2 operation). Phase 3 has two operation periods in each year. Each run has a name that begins with the calendar year followed by the letters "ab" or "c" to indicate the operation period "from the end of the winter shutdown to the beginning of the summer shutdown" and "from the end of the summer shutdown to the beginning of the winter shutdown," respectively. The histories of beam currents and luminosity for Phase 3 are shown in Figure 1. By the end of the 2022ab run, the β_y^* had gradually been squeezed and finally reached 1 mm in normal physics runs and 0.8 mm in a 2-week trial. Peak luminosity reached 4.7×10^{34} cm^{-2}s^{-1} and the total integrated luminosity was 428 fb^{-1}. After the 2022ab run, we enforced a long shutdown 1 (LS1) to perform an accelerator upgrade, and the 2024ab run was resumed in January 2024.

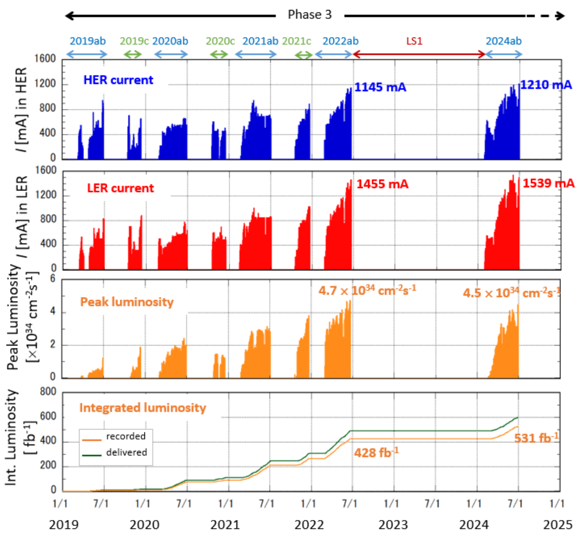

Figure 1: Histories of the high-energy ring (HER) beam current, low-energy ring (LER) beam current, and peak and integrated luminosities

2. Major upgrade items during LS1

The main challenges of luminosity frontier machines found before the LS1 are:

- C1: Shorter beam lifetime than expected in the design phase
- C2: Lower bunch current limit due to the beam instabilities
- C3: Low machine stability
- C4: Low injection efficiency
- C5: Severe beam–beam effect (beam blow-up) at high-bunch current

The transverse mode coupling instability (TMCI), which is one of the factors limiting the bunch current in C2, is caused by the high impedance of beam collimators. As the apertures at the collimators are much smaller than the design values to suppress high background (BG) noise to Belle II, the impedance of the collimators becomes larger than expected. Regarding C3, one of the obstacles to maintaining stable machine operation is the sudden beam loss (SBL), where some part of the bunch train is lost within a few turns without considerable bunch oscillation. When the

SBL occurs, a beam abort is typically requested by beam loss monitors. Although the beam abort system dumps the beam safely to protect the machine, it is difficult to prevent uncontrollable beams from damaging the collimator jaws because the SBL phenomenon is too fast. To make matters worse, the damaged collimator jaws increase the impedance (C2) and the BG. The cause of the SBL was unclear, but it was known that the SBL had the following characteristics before the LS1:

- The SBL occurred in both the LER and HER cases
- The SBL occurred when the bunch current exceeded 0.65 mA/bunch
- The bunch current threshold of the SBL seemed to be reduced when extensive damage occurred in the collimator jaws

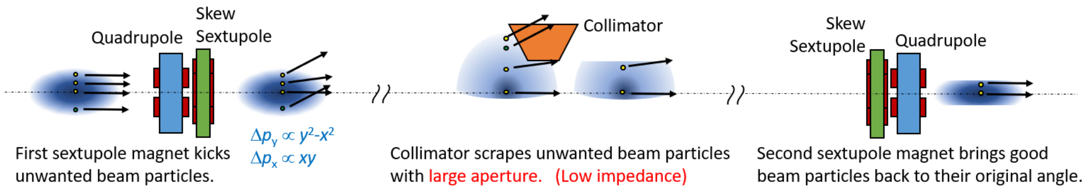

Figure 2: Conceptual diagram of the nonlinear collimation scheme

To address C2, during the LS1, the world's first nonlienar collimator (NLC) system [3] was installed into the Oho straight section in LER, where the wiggler section used to be. The conceptual diagrams of the NLC scheme are shown in Figure 2. The NLC system consists of a pair of skew sextupole magnets and a vertical collimator at the midpoint of the skew sextupole pair. The vertical kick angle of the first skew sextuple is proportional ($y^2 - x^2$), where x and y are the horizontal and vertical positions from the center of the skew sextupole. As the vertical beam halo is expanded substantially in one vertical direction by the first sextupole, it is possible to collimate the vertical halo components by the collimator with a larger aperture than that which operated based on a conventional collimation scheme. Subsequently, the second skew sextupole kicks back the good beam particles to their original angle. The impedance of the NLC must be smaller than that of the conventional collimators owing to its larger aperture, so it can relax the TMCI bunch current limit. Approximately 50 wiggler magnets were removed to make space for the NLC section. A pair of new skew sextupoles were installed, while the quadrupole magnets were reused. The vertical collimator in the NLC section (D05V1 collimator) was relocated from another section. The NLC was also expected to be effective in reducing the SBL if something that happened in the small-aperture collimators induced the SBL (C2, C3). Regarding the SBL, new fast beam loss monitors were installed near the collimators to detect the SBL and abort the beam as fast as possible. To check whether any discharges occurred in the collimators with the SBL, acoustic sensors were installed on some of the vertical collimators. Furthermore, the bunch oscillation recorder used to record the behavior of the bunches just before the beam abort was strengthened. To address C4, the HER injection point was modified to enlarge the horizontal aperture because high-residual radioactivity had been observed at the injection point. The beam pipes at the injection point were replaced with new ones with larger horizontal apertures. A septum magnet at the most downstream location was also replaced with a new one to provide a better magnetic field. In the BT, alignment of the magnets was performed. At the most downstream location of the BT, the beam position monitor was replaced with a new one. There were other upgrade items such as the change of the collimator jaw to a robust one (carbon collimator jaw) in LER, the installation of new pulsed quadrupole magnets and fast kickers at the Linac, radiation shield enhancement near Belle II, and others. The damaged collimator jaws with high impedance were also replaced with new ones.

3. Highlights of the 2024ab run

The overview of the 2024ab run is shown in Figure 3. It was started on 29 January 2024 with vacuum scrubbing with a beam dose of ~100 Ah. The physics run was resumed with the β_y^* of 8 mm on 20 February. Following machine tuning and machine studies, the β_y^* was squeezed from 8 mm to 3 mm, and finally to 1 mm in mid-March. Subsequently, the beam currents were gradually increased by maintaining the β_y^* value at 1 mm. The number of bunches was fixed mostly at 2346 to make machine tuning easier. However, as the beam currents increased, the SBL occurred again frequently, especially in the LER, and it became difficult to maintain stable machine operation and increase the beam currents. On 22 April and 6 May, beam aborts in conjunction with the SBL in the LER damaged the pixel detector (PXD) at the innermost part of Belle II, which made 10% of PXD unusable. After these events, identification of the cause of the SBL became the most important and urgent task, and more time was spent on studies on the SBL. Since mid-June the physics run that aimed to set a new luminosity record has resumed. The β_y^* value was squeezed to 0.9 mm and the number of the bunch was reduced to 2246. Finally, the peak luminosity reached 4.47 × 10^{34} $cm^{-2}s^{-2}$ which was approximately 95% of the luminosity record achieved in the 2022ab run. The 2024ab run ended on 1 July 2024.

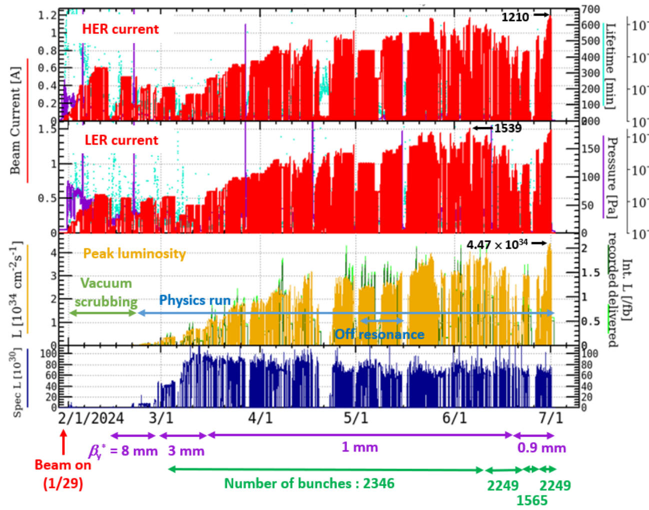

Figure 3: 2024ab run overview

3.1 SBL

Numerous new findings were noted regarding the SBL, as follows:

- The SBL occurs when single beams are used or after collisions, even bunch currents lower than 0.65 mA/bunch and at the β_y^* values of 1 and 3 mm
- Higher total currents result in more frequent sudden beam losses.
- Vertical beam size increases when SBL occurs.
- In most cases, the pressure spikes in the wiggler sections were observed, where beam pipes with electron-clearing electrodes [4] were installed to mitigate the electron cloud in the LER.
- Knocking the beam pipes at the wiggler sections by a "knocker" can cause an SBL, and knocking beam pipes seems to be effective in reducing an SBL.

These findings indicated that dust can be the cause of SBL. Additionally, numerous tiny dust particles were observed in the beam pipe with the electron-clearing electrode removed from the wiggler section for the NLC installation in the LER.

3.2 First trial of NLC

Belle II BG caused by the storage beam and beam lifetime were compared when the NLC (D05V1) and a conventional collimator (D06V1) used the same effective collimation gap of 64σ_y, which corresponded to the D05V1 and D06V1 values of 3.5 mm and 2.4 mm, respectively, where σ_y is the vertical beam size at each collimator. Figures 4(a) and 4(b), respectively, show the storage beam BG and the beam lifetime measured by varying the beam current. The D05V1 suppressed the storage beam BG to a greater extent than the D06V1 with the same effective collimation gap, although it did not reduce the beam lifetime. Furthermore, the vertical beam blow-up observed with D06V1 was not observed with D05V1, as shown in Figure 4(c). This indicates that the NLC reduced the impedance, which caused the beam to blow up. Meanwhile, it remains to be confirmed whether the NLC can also suppress the BG generated by the injected beam.

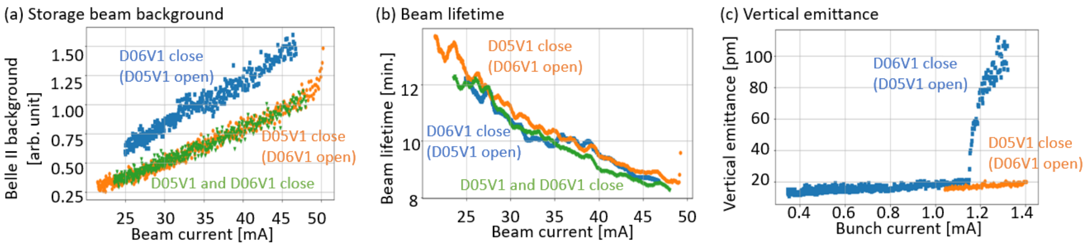

Figure 4: Comparison between the nonlinear collimator and the conventional collimator on (a) storage beam background, (b) beam lifetime, and (c) vertical beam blow-up (vertical emittance)

3.3 Injection and maximum beam currents

The typical injection efficiency of the HER had been 30–40% for most of the 2024ab run and reached 80% for LER. However, a considerable improvement was achieved, and the injection efficiency was maintained at 60–80% during the last 2 weeks of the run. The main factors responsible for the improvement were the "precise measurement of the injection beam orbit and its correction," "fine optics matching between the MR and the BT," and the "benefits of the LS1 upgrade." The maximum beam current was 1.2 A, although the target was 1.4 A. However, it will be possible to increase the beam current further in the subsequent run. The maximum beam current in the LER was 1.5 A, although the target was 1.8 A. It was newly found that injection degradation occurred owing to the beam–beam interaction effect at high-bunch currents. It was also found that the lower betatron tune could improve the injection efficiency. For both rings, a two-bunch injection—where two bunches were injected in a single pulse—was performed to increase the injection rate. However, as the 2nd bunches caused the beam to abort frequently, it could not be maintained for a long period. For further beam current increases, it was necessary to maintain a stable two-bunch injection.

3.4 Luminosity

The peak luminosity was 4.47 × 10^{34} cm^{-2}s^{-1} with a specific luminosity of 5.9 × 10^{31} cm^{-2}s^{-1}mA^{-2}, β_y^* of 0.9 mm, beam currents of 1180 mA (HER)/1450 mA (LER), number of bunches of 2249, a bunch current product ($I_{b+}I_{b-}$) of 0.338 mA^2, and crab waist ratios of 60% (HER) and 80% (LER). The beam–beam study and high bunch current study led to the following findings:

- Crab waist was effective in increasing luminosity and $I_{b+}I_{b-}$

- Single beam vertical blow-up was observed over 0.5 mA/bunch in both rings
- LER vertical blow-up owing to the beam–beam effect was observed
- Lowering the horizontal tune improves the LER injection efficiency and helps increase the beam current
- Peak luminosity reached 1.38×10^{34} cm^{-2}s^{-1} with 393 bunches. (Figure 5)

These findings indicate that the luminosity could reach 8×10^{34} cm^{-2}s^{-1} at increasing bunch numbers up to 2346, even if the beam blowup was not suppressed.

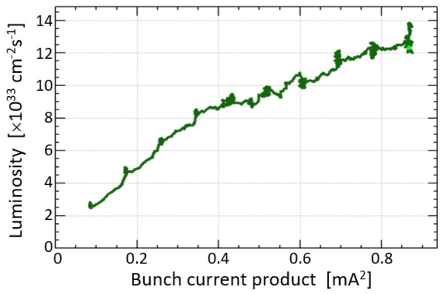

Figure 5: Luminosity with 393 bunches

4. Summary and Future Plan

The first commissioning of the SuperKEKB after the LS1 was conducted from 29 January to 1 July 2024. The peak luminosity was 4.47×10^{34} cm^{-2}s^{-1} and the integrated luminosity was 103 fb^{-1}. The β_y^* value was finally squeezed down to 0.9 mm. The 2024ab run yielded numerous findings and achievements. The effectiveness of the NLC was demonstrated for the first time in the world. The HER injection efficiency was finally improved to ~80% thanks to the injection point upgrade and fine-tuning. The SBL was still the biggest problem. However, several new findings suggest that the dust from the beam pipes with the electron-clearing electrode may be the cause of the SBL. New challenges were also identified, such as the strong beam–beam effect, which makes it difficult to increase the beam current in the LER.

During the summer shutdown after the 2024ab run, some beam pipes with the clearing electrodes on the top side will be turned upside down to prevent the dust from falling. Additional works are also planned to achieve more stable two-bunch injections for both rings. The 2024c run is scheduled to begin on 9 October 2024, during which we will aim to achieve a luminosity of 8×10^{34} cm^{-2}s^{-1} by increasing the beam currents and more by squeezing β_y^*.

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