PROCEEDINGS OF SCIENCE

SuperKEKB Status

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SuperKEKB is a double-ring collider consisting of a 7-GeV electron ring (HER) and a 4-GeV positron ring (LER) with a circumference of approximately 3 km, constructed by reusing the KEKB tunnel. To further increase the peak luminosity, a nanobeam scheme with a large crossing angle was adopted. Electrons and positrons collide at a larger horizontal crossing angle while maintaining a bunch length that is approximately the same as that of the KEKB. Therefore, the actual collision area could be considerably shorter than the bunch length. This mitigates the hourglass effect that results from collisions over the entire length of the bunch and allows a strong vertical squeeze to increase the luminosity. SuperKEKB was commissioned for four months in 2022 and has now entered Long Shutdown 1 (LS1) for approximately 15 months. Various upgrades are underway. The beam currents increased gradually, and maxima of 1145 and 1460 mA were stored in the HER and LER, respectively. The peak luminosity of 4.7×10^{34} cm^{-2} s^{-1} with a vertical beta function (β_y^*) of 1 mm at the interaction point (IP) was achieved in June 2022, breaking the previous year's SuperKEKB world record. This paper presents recent progress and addresses the challenges and issues that need to be tackled in conjunction with the upgrade efforts during LS1, aiming to further enhance luminosity performance.

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1. Introduction

SuperKEKB is an electron-positron double-ring circular collider with an innovative "nanobeam scheme" implemented for the first time worldwide [1]. Its primary objective is to increase the collision frequency per unit area per second, known as luminosity, which is one of the most crucial parameters for a collider. This aims to improve upon the 2.1 × 10^{34} $cm^{-2}s^{-1}$ achieved by its predecessor, the KEKB collider, up to several tens of times higher luminosity. The high statistics provided by SuperKEKB contribute to the search for new phenomena beyond standard particle physics models.

The operation of SuperKEKB Phase 3 commenced in March 2019, with a fully instrumented Belle II detector. The crab waist scheme was implemented in April 2019 to enhance beam performance. In 2020, SuperKEKB surpassed the luminosity record of 2.11 × 10^{34} cm^2s^{-1} achieved by its predecessor, KEKB, with vertical and horizontal beta functions at the IP set at 1 mm and 80 mm (LER)/60 mm (HER), respectively. Thanks to the nanobeam scheme, the peak luminosity record was surpassed with smaller beam currents than those used at KEKB. In June 2022, SuperKEKB achieved a new world record for a peak luminosity of 4.7 × 10^{34} cm^2s^{-1} with a β_y^* of 1 mm at the collision point [2]. Figure 1 compares the peak luminosity and average beam currents in the HER and LER for KEKB and SuperKEKB. Table 1 summarizes the machine parameters as of June 8th, 2022, with design parameter values indicated in parentheses.

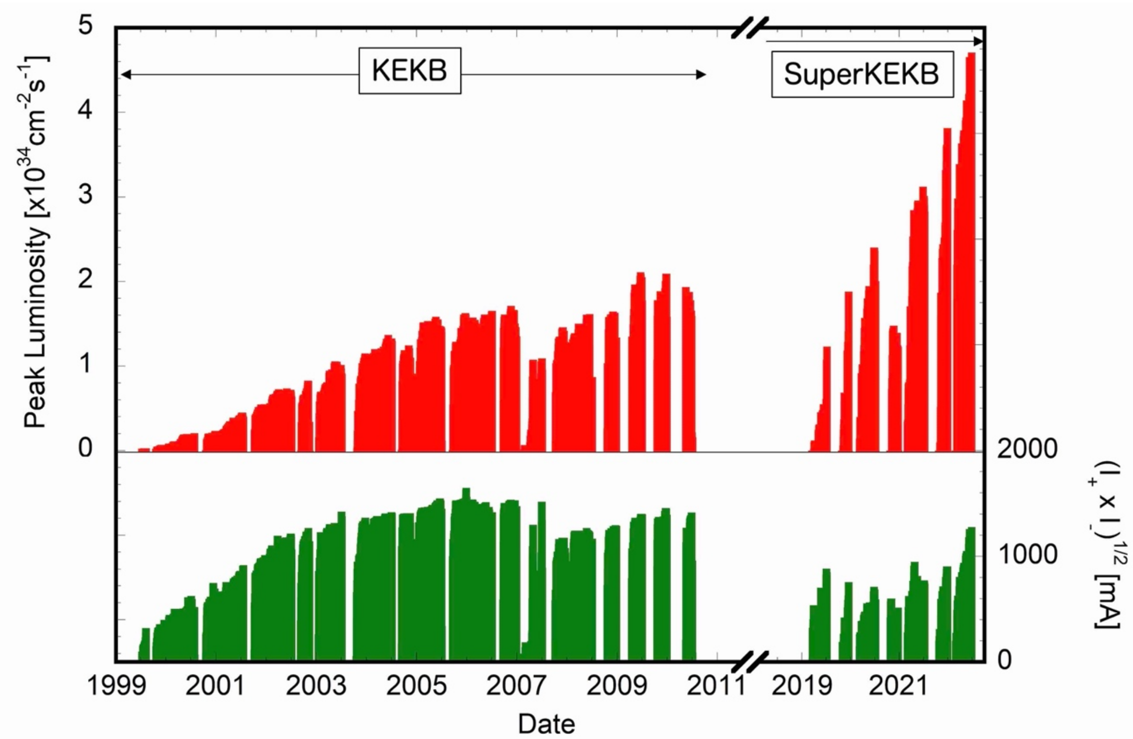

Figure 1: Peak luminosity achieved (top) and the average of the beam currents in the HER and LER for KEKB and SuperKEKB, respectively.

Table 1: Machine parameters as of June 8th, 2022, with the design values indicated in parentheses.

Papameter	LER	HER	unit
Beam current	1321 (3600)	1099 (2600)	mA
# of bunches	2249 (2500)		
Bunch current	0.587	0.489	mA
β_x^*/β_y^*	80/1.0 (32/0.27)	60/1.0 (25/0.30)	mm
Beam-Beam Parameter ξ_y	0.0407 (0.088)	0.0279 (0.081)	
σ_y^*	0.215 (0.048)	0.215 (0.062)	µm
tunes (x/y)	44.525/46.589	45.532/43.573	
Specific luminosity($\times 10^{31}$)	7.21		$cm^{-2}s^{-1}/mA^2$
Luminosity($\times 10^{34}$)	4.65 (60)		

While making steady progress, SuperKEKB encounters several challenges as a luminosity frontier machine. These include issues related to the efficiency and stability of beam injection into the main ring, collimation and machine protection strategies, safe increases in beam currents, reduction of the horizontal and vertical beta functions at the IP, and overcoming various beam instabilities, such as sudden beam loss (SBL). The next section provides a detailed description of some of the problems and challenges faced in luminosity tuning.

2. Challenges

Two approaches were adopted to increase peak luminosity: one involved increasing the stored beam currents, and the other focused on squeezing the HER and LER beams both horizontally and vertically at the IP by adjusting the horizontal and vertical beta functions at the IP. The concept of the luminosity increase strategy is illustrated in Fig. 2.

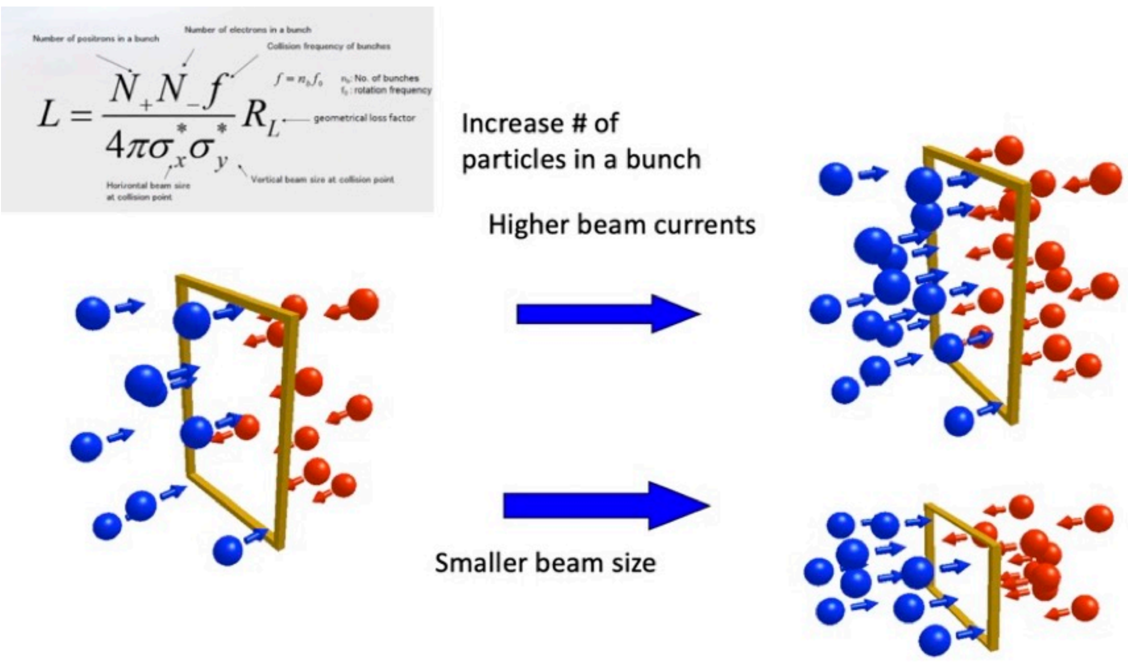

Figure 2: Two approaches for increasing the peak luminosity are illustrated.

Since the number of bunches had already reached the design value, the need arose to increase the bunch current to boost the stored beam currents in both the HER and LER. However, this proved challenging in the 2022 operation due to issues like SBL accompanied by collimator damages and sometimes by quenches of the final focus quadrupole magnet system (QCS). Balancing the charge delivered from the LINAC, injection efficiency to the main ring, and beam lifetime also emerged as a significant concern. As the horizontal and vertical beta functions decrease, the injection efficiency and lifetime of the stored beam currents decrease as well.

2.1 Collimators

SuperKEKB main-ring collimators were strategically placed between the injection point and the IP to reduce detector background at the IP and protect the accelerator components, as depicted in Fig. 3.

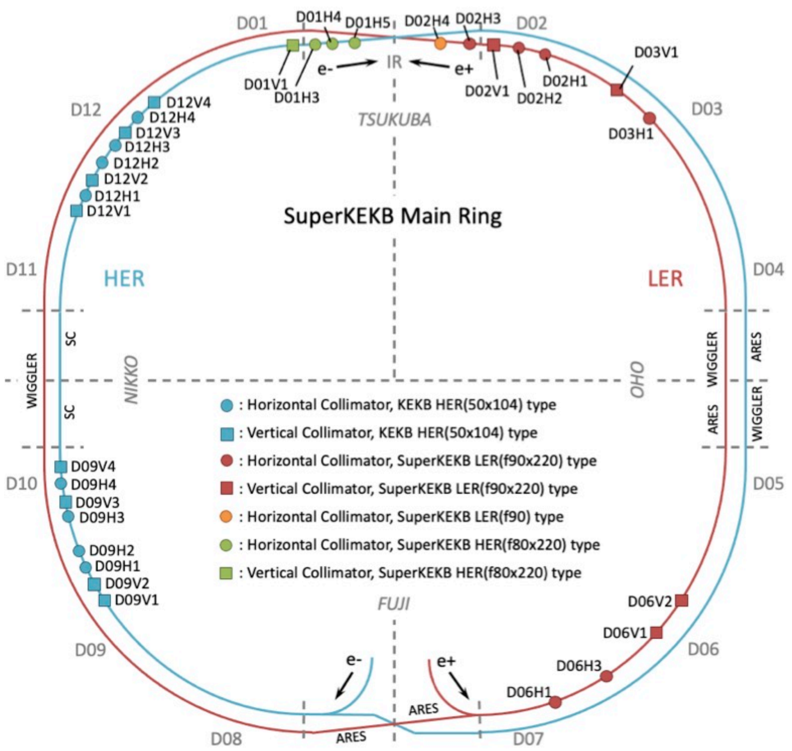

Figure 3: SuperKEKB collimator locations for HER and LER. V and H indicate vertical and horizontal collimators, respectively.

The collimator aperture is controlled remotely using movable "jaws" made of tungsten. Figure 4 shows the SuperKEKB horizontal and vertical collimators, respectively. A smaller aperture results in reduced detector background but also leads to a shorter lifetime and lower injection efficiency. When the collimator heads are too close to the beam, they are sometimes directly hit by the beam, resulting in damage, as shown in Fig. 5. These damaged collimators become impedance sources that may trigger SBL.

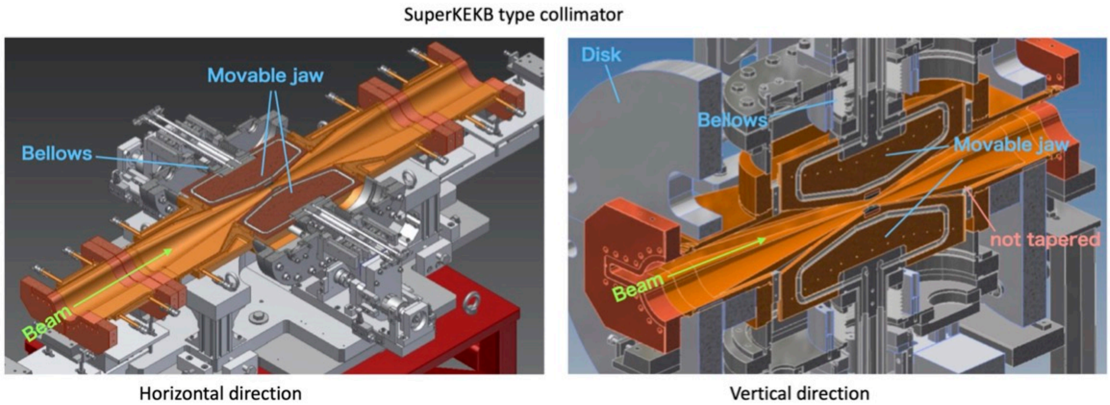

Figure 4: SuperKEKB horizontal (left) and vertical (right) collimators, movable jaws are controlled remotely.

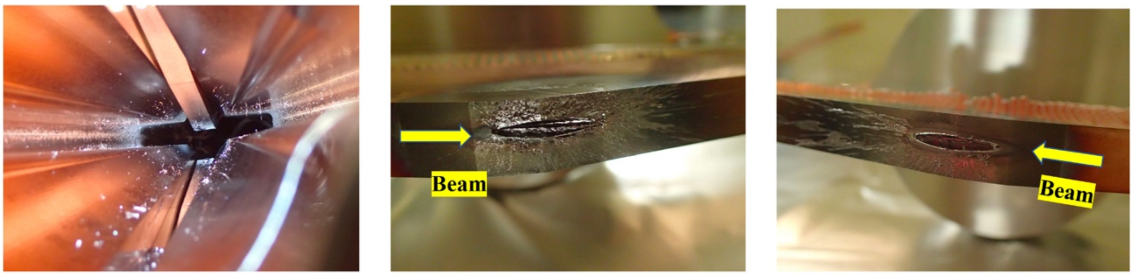

Figure 5: Damaged collimator heads by a direct hit by beam.

2.2 SBL

Beam aborts that lead to collimator damages and/or QCS quenches are more likely to occur when the bunch current exceeds a threshold of 0.7 mA, a phenomenon more pronounced in the LER. Figure 6 summarizes the LER stored current, number of bunches in the main ring, and the bunch current. The SBL incidents are also indicated in Fig.6. It can be seen that the threshold for SBL decreases and SBL occurs more frequently toward the end of June.

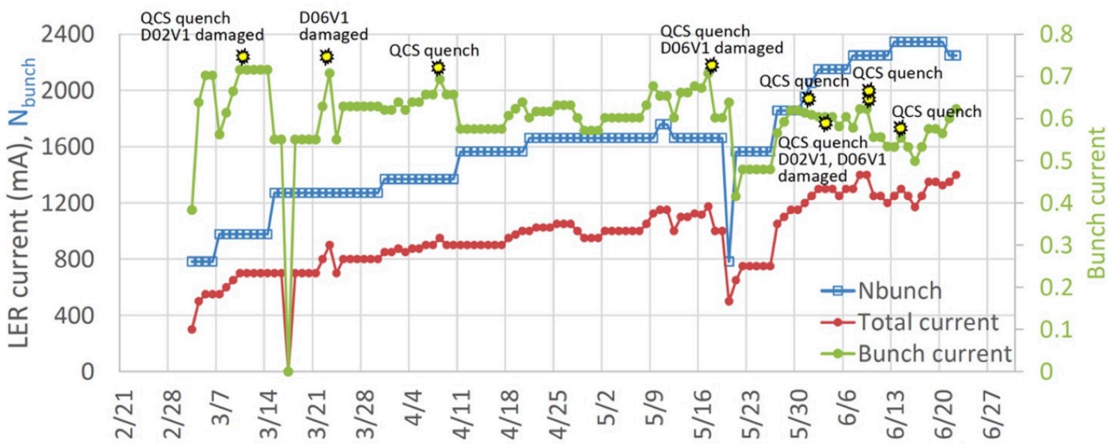

Figure 6: Stored beam current, number of bunches, and bunch current plotted against time.

Regarding SBL, several observations were made during the 2022 beam commissioning:

- Beam loss within a few turns (1 turn = 10 μs), suddenly, without any indication of beam-size blow up or instability.
- It appeared to occur more frequently in the 2022 run when the bunch current exceeded ~0.7 mA, whereas no such threshold was observed in the 2021 run.
  - → What are the differences between 2021 and 2022?
  - → One clear difference is that collimators were healthy in 2021.
  - → On March 11, 2022, the QCS was quenched, and one of the LER collimators, D2V1, near the IP, was damaged.

From these observations, it appears that collimator damage is the most likely cause of SBL. Figure 7 shows the bunch oscillation data, bunch current monitoring data, and beam loss data when SBL occurred. The beam remained stable for approximately a few turns before the beam abort, leading to the term "Sudden Beam Loss." Several assumptions have been proposed to explain SBL, with the "Fireball" theory/assumption [3] being the most recent and plausible candidate, as conceptually depicted in Fig. 8. According to this theory, when a micro-particle with a high sublimation point (such as tungsten) is heated by the beam-induced field, it transforms into a "fireball" and lands on the surface with a lower sublimation point (such as the copper beam pipe). Plasma is generated around the fireball in an environment with a high RF field, resulting in a macroscopic vacuum arc and potentially significant interactions with the beam particles, leading to severe damage to the collimator head. Coating tungsten with copper may prevent the occurrence of the fireball phenomenon if proximity between copper and tungsten is indeed a necessary condition.

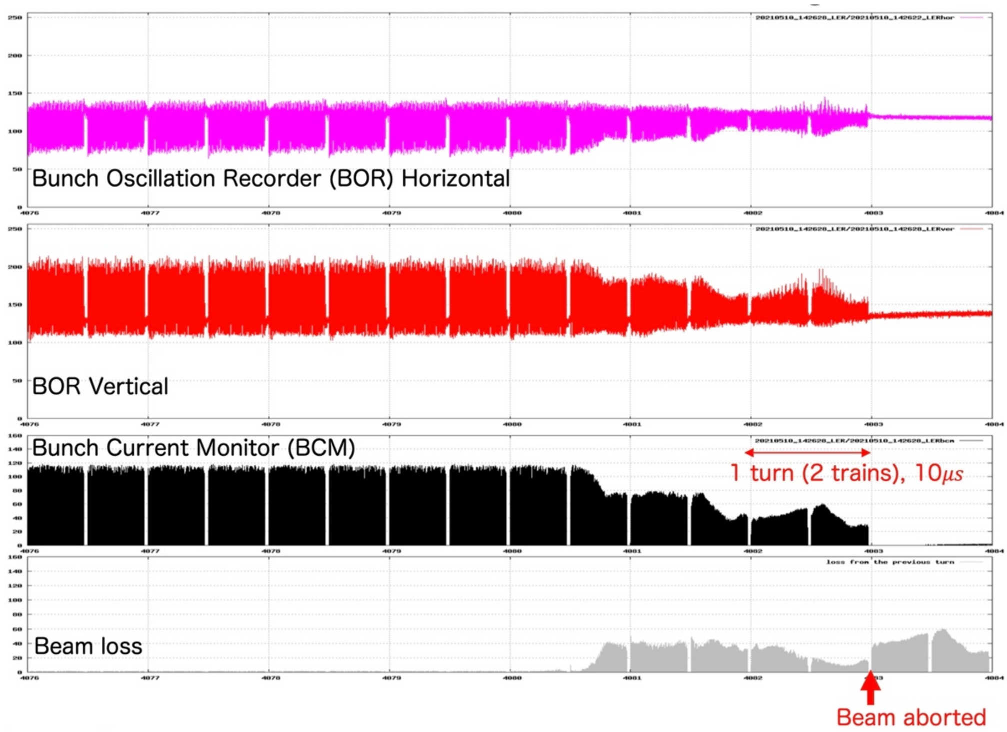

Figure 7: Bunch Oscillation Recorder data in horizontal and vertical directions and the bunch current monitor dataplotted during the occurrence of beam abort took.

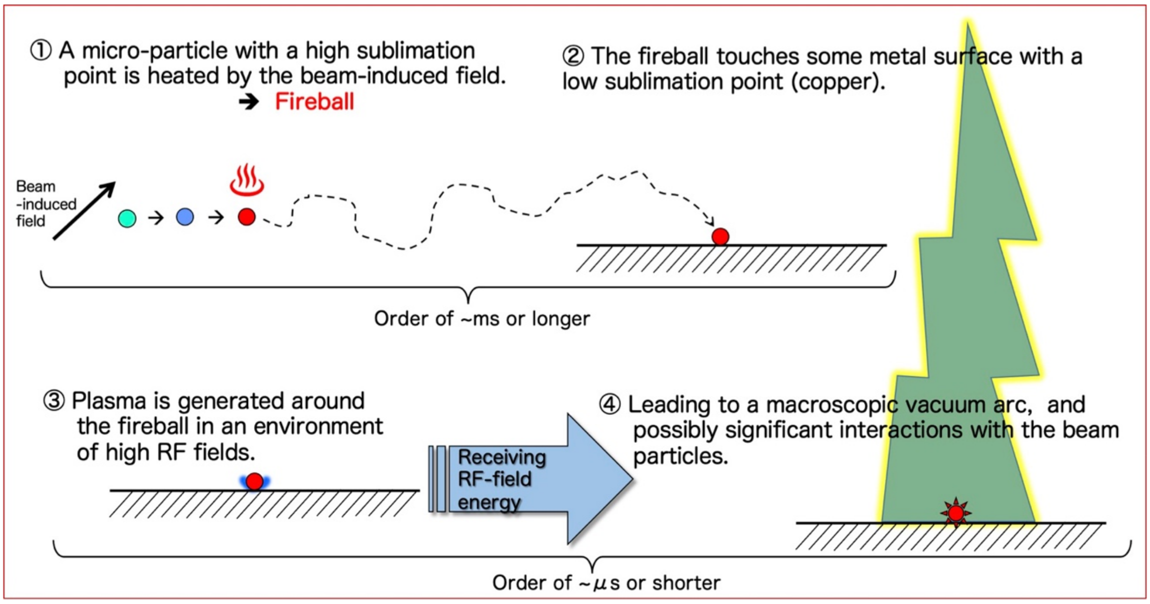

Figure 8: Conceptual diagram of "Fireball" theory.

2.3 Detector background

Various sources contribute to beam instability, and Transverse Mode Coupling Instability (TMCI) is one of them. The apertures of the vertical collimators can induce TMCI. The TMCI threshold will likely be lower than the design bunch current of 1.44 mA when we reduce β_y^* to 0.6 mm. The new beam collimation scheme called "Non-linear collimator (NLC)" may help increase the TMCI limit while maintaining larger collimator apertures and reducing BELLE II background. Details about NLC and other countermeasures during LS1 are provided in the next section.

3. Countermeasures during LS1

Various Several countermeasures were implemented during LS1, as depicted in Figure 9 for the main ring. These measures include: 1) Installing an NLC in the LER to reduce impedance and detector backgrounds. 2) Adding additional radiation shielding near the IP and its vicinity. 3) Replacing heavy metal collimator heads with carbon for enhanced robustness in certain collimators. 4) Coating the collimator heads with copper to minimize impedances and reduce the occurrence of fireball incidents. 5) Replacing the beam pipe with a wider aperture at the HER injection point to improve injection efficiency. 6) Replacing some of the RF cavities for more stable beam operation.

Notably, SuperKEKB implemented NLC for the first time in the world. The NLC employs a non-linear magnetic field generated by the first skew sextupole magnet to temporarily enlarge the beam size just before the collimator. This allows for effective collimation without the collimator jaw coming into contact with the beam core. After the collimator has removed unwanted portions of the beam, the beam is restored to its original size using the non-linear magnetic field generated by the second skewed sextupole magnet, as schematically shown in Figure 10.

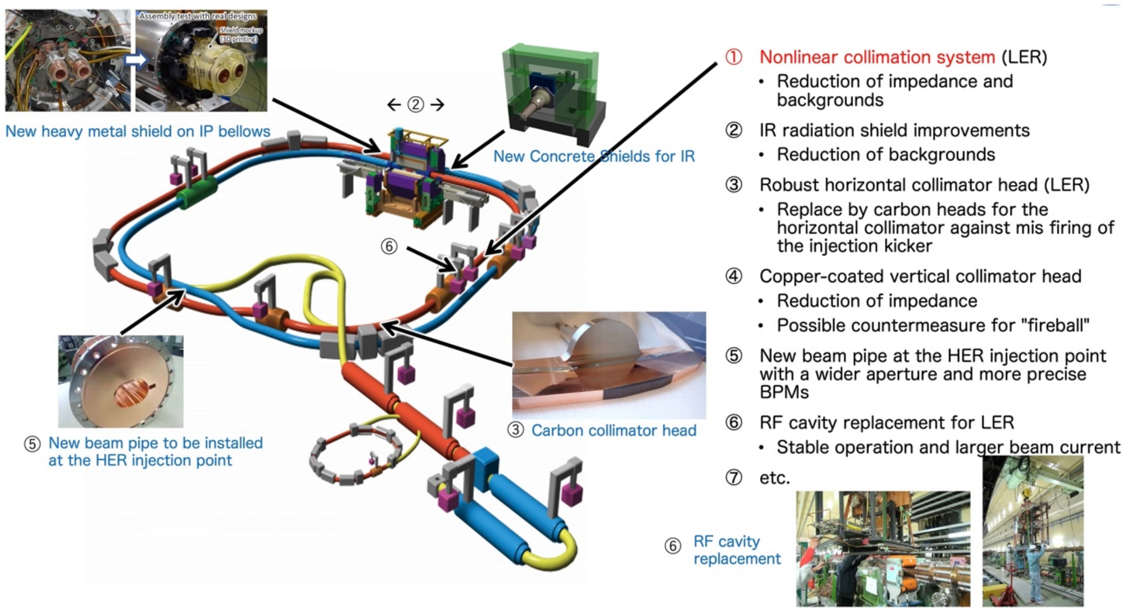

Figure 9: Major steps in the MR during LS1.

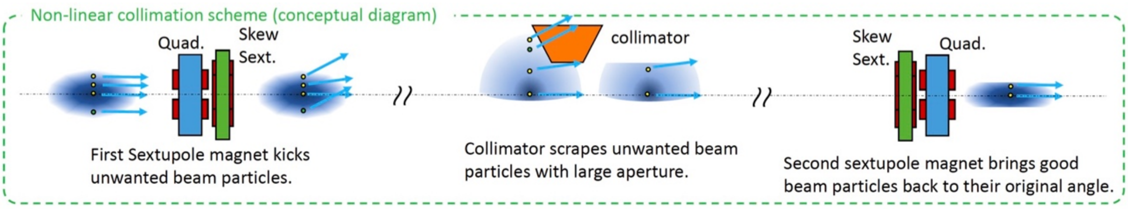

Figure 10: Non-linear Collimation scheme with a set of skew sextupole magnets.

4. Strategy after LS1

Our plan is to resume beam commissioning in December 2023, with the goal of achieving a peak luminosity of $1.0 \times 10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$ s expeditiously as possible. We intend to increase the bunch current and enhance luminosity at higher bunch currents by reducing the beta functions at the IP. As such, we will need to conduct various machine studies and ongoing simulations. To provide guidance, we have plotted specific luminosity, which is the luminosity per beam current product, against the beam current product for different β_y^* values at the IP in Fig.11. The data points are represented by different colors corresponding to different β_y^* values. Our strategy involves reducing β_y^* and increasing the bunch current to attain higher luminosity levels.

5. Summary

SuperKEKB has consistently set and updated world records in peak luminosity, despite facing certain challenges, as outlined below.

- Difficulty in increasing bunch current
  - Sudden Beam Loss
  - Detector background, collimator damage
- Operation at smaller β_y^* is a challenge.
  - Balance between the injection charge, injection efficiency, beam quality (emittance) of the injected beam, MR beam lifetime, and detector background.

During LS1, several modifications and improvements were implemented. SuperKEKB is scheduled to resume operation in December 2023, with collisions planned for February. We are committed to achieving a peak luminosity of $1 \times 10^{35} cm^{-2} s^{-1}$ as swiftly as possible. Our long-term goal is to achieve even higher luminosity levels by increasing stored beams and reducing β_y^*.

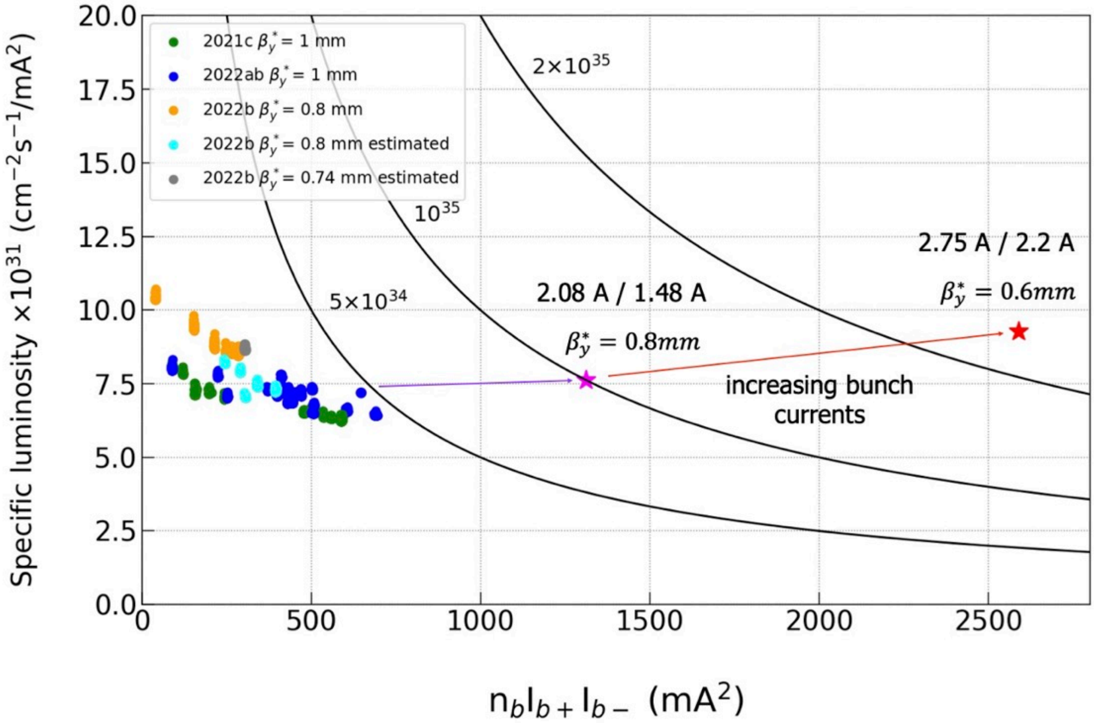

Figure 11: Luminosity plotted against the product of beam currents for different β_y^*.

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