

First experimental report of nonlinear collimator in the SuperKEKB

Shinji Terui^{✉,*}, Yoshihiro Funakoshi[†], Naoko Iida, Takuya Ishibashi[✉], Haruyo Koiso,
Akio Morita, Shu Nakamura[✉], Yukiyoishi Ohnishi[✉], Hiroshi Sugimoto, Kyo Shibata,
Kenta Uno[✉], and Mulee Yao[✉]

High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Giacomo Broggi[✉]

Sapienza University of Rome, Rome, Italy

Katsunobu Oide[✉]

University of Geneva, Geneva, Switzerland

Andrii Natochii[✉]

Brookhaven National Laboratory, Upton, New York, USA

Qingyuan Liu[✉]

University of Hawaii, Honolulu, Hawaii, USA



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SuperKEKB collimator system protects the superconducting final focusing magnets (QC1 and QC2) from quenching caused by beam halo particles. For effective shielding, the minimum aperture of vertical collimators is set smaller than the physical aperture of QC1. However, such collimators become dominant sources of beam coupling impedance, which can limit the maximum beam current due to impedance-driven instabilities. To address this issue, a nonlinear collimator (NLC) was introduced in February 2024. NLC is designed to reduce both beam backgrounds and collimator impedance, thereby suppressing beam instabilities caused by short-range wakefields. In this paper, we describe the results on impedance effects, beam background reduction, and beam lifetime when the nonlinear collimation system is turned on and off. These results validate the NLC concept and offer a promising approach for future high-luminosity colliders.

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I. INTRODUCTION

SuperKEKB is an electron-positron collider that aims to achieve a luminosity far exceeding that of its predecessor, KEKB, for exploring new physics beyond the Standard Model [1]. The collider consists of two main rings (MRs): a 7 GeV electron ring, called the high-energy ring (HER), and a 4 GeV positron ring, called the low-energy ring (LER) [2]. The design parameters and the values achieved on the last day of the 2024ab run (January 30 to June 27, 2024) at SuperKEKB are shown in Table I.

SuperKEKB aims to achieve ultrahigh luminosity by combining small beam sizes at the interaction point with

high beam currents and by exploiting the crab waist collision scheme [3,4]. A major challenge in this pursuit is the suppression of beam-induced backgrounds affecting the Belle II detector. To mitigate these backgrounds, both the HER and LER are equipped with multiple movable beam collimators. The luminosity of SuperKEKB is the highest worldwide; however, its operation has several limitations. To address these limitations, studies on developing possible mitigation strategies are ongoing. A nonlinear collimator (NLC) [5–9] was installed to reduce one of the major limitations—impedance and beam-induced backgrounds. This paper presents an overview of this NLC and reports the results of the first beam study.

Herein, to emphasize the importance of the collimator impedance, we summarize the insights gained from other colliders, wherein collimator designs have been systematically optimized to reduce both the geometric and resistive-wall components of the beam coupling impedance. At the LHC, extensive efforts—encompassing mechanical design, material selection, and embedded diagnostics such as BPMs—have been devoted to minimizing the impedance

*Contact author: sterui@mail.kek.jp

†Contact author: yoshihiro.funakoshi@kek.jp

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TABLE I. Design parameters and the values achieved in the 2024ab run at SuperKEKB.

Parameters	Units	Design		2024ab run	
		LER	HER	LER	HER
Beam currents	A	3.6	2.6	1.39	1.11
Energy	GeV	4.0	7.0	4.0	7.0
Number of bunches			2500		2249
β_x^*/β_y^*	mm	32/0.27	25/0.30	80/0.9	60/0.9
Luminosity	cm ² s ⁻¹		8×10^{35}		4.47×10^{34}

[10–12]. Similar challenges have been identified in lepton colliders, including PEP-II, DAFNE, and KEKB, where low-impedance collimator development and studies of beam-collimator interactions have been conducted [13–15]. In future high-luminosity colliders, the impact of collimator impedance on beam dynamics is also expected to be significant, which has motivated dedicated collimation design and wakefield studies [16].

II. OVERVIEW OF NONLINEAR COLLIMATOR FOR SUPERKEKB

A. Outline of nonlinear collimator design

SuperKEKB has four straight sections, and NLC was installed in the Oho straight section in the LER. The lattices of NLC section are shown in Fig. 1. In the SuperKEKB NLC, a pair of skew-sextupole magnets of equal strength, named SNAP.1 and SNAP.2, is coupled using a $-I'$ transfer matrix. The $-I$ transformation corresponds to a configuration in which the phase advance between the two nonlinear elements is π , and under this condition their first-order nonlinear kicks cancel each other. In real SuperKEKB optics, however, the transfer matrix R between the two nonlinear elements does not become exactly $-I$, because the chromaticity must be properly adjusted. As a result, the off-diagonal elements R_{21} and R_{43} are nonzero, and the overall configuration is therefore referred to as $-I'$

[17]. Using the $-I'$ arrangement, the influence on the beam core is minimized, while the nonlinear collimation effect on large-amplitude particles is maximized.

The Hamiltonian of a skew-sextupole magnet with a thin lens approximation is presented by the following equation:

$$H_s = -\frac{K_s}{6}(y^3 - 3x^2y). \quad (1)$$

This kick by a skew-sextupole is expressed with the thin lens approximation as

$$\Delta p_x = -\frac{\partial H_s}{\partial x} = -K_s xy, \quad (2)$$

$$\Delta p_y = -\frac{\partial H_s}{\partial y} = \frac{K_s}{2}(y^2 - x^2). \quad (3)$$

Here, Δp_x and Δp_y are the kicks in the horizontal and vertical planes, respectively. The variables x and y are the horizontal and vertical orbit offsets at the skew-sextupole, respectively. The strength of the skew-sextupole is K_s . Thus, the vertical beam orbit at the collimator between the two skew-sextupoles is expressed by the following equation. R_{34} denotes the transfer-matrix element that transports the vertical angle at the skew-sextupole to the vertical displacement at the collimator:

$$y_c = R_{34}\Delta p_y = \frac{K_s}{2}\sqrt{\beta_{y,c}\beta_{y,s}}\sin\varphi_y(y^2 - x^2). \quad (4)$$

The vertical β function at the D05V1 ($\beta_{y,c}$) should be reduced to the extent possible to increase the threshold of the bunch current for beam instability. As is well known, this is because the transverse kick force received by the beam is the product of the β function and the kick factor [18]. Therefore, the vertical β function at the skew-sextupole magnet ($\beta_{y,s}$) becomes extremely large. $\sin\varphi_y$ is the vertical phase difference between the skew-sextupole magnet and collimator, set to $\pi/2$ in SuperKEB; thus, Eq. (4) can be revised as

$$y_c = \frac{K_s}{2}\sqrt{\beta_{y,c}\beta_{y,s}}(y^2 - x^2). \quad (5)$$

The vertical beam halo is kicked vertically by the nonlinear magnetic field of the upstream skew-sextupole

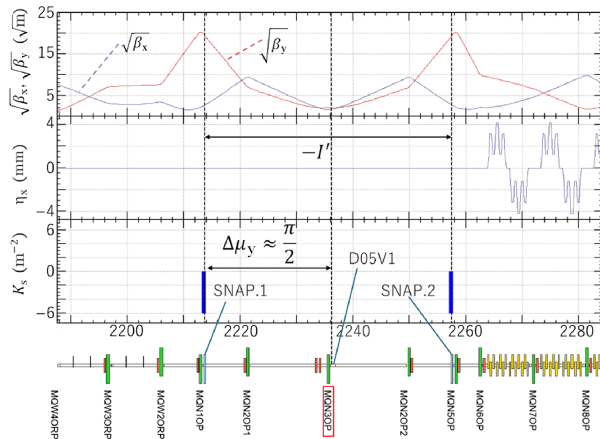


FIG. 1. Layout of the design lattice for NLC.

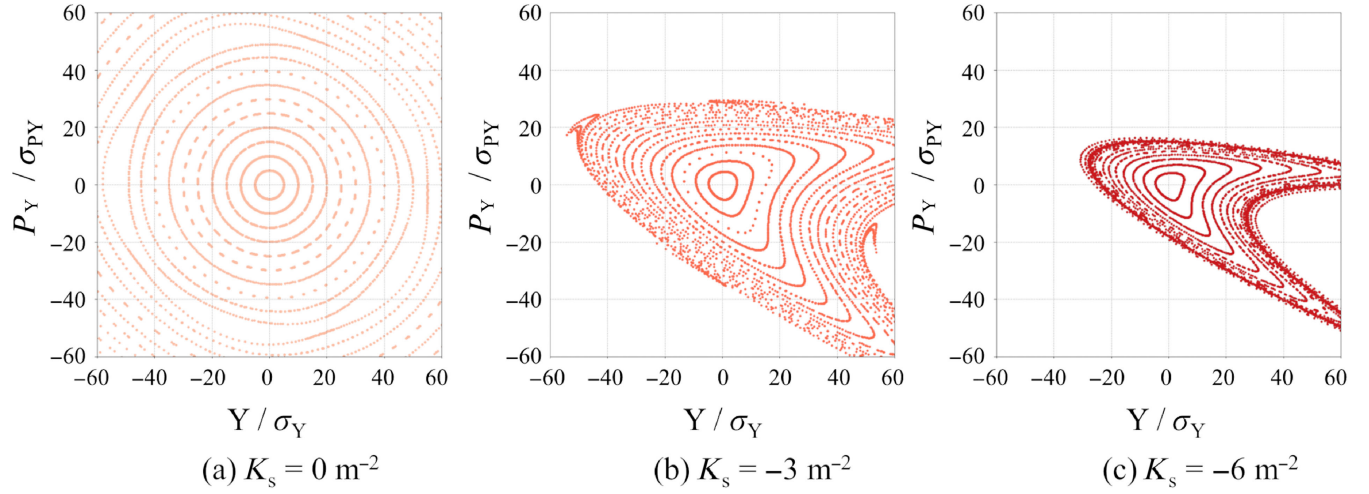


FIG. 2. Vertical phase space derived from calculations at D05V1 collimator, with the horizontal and vertical axes representing the vertical position and vertical momentum, respectively, for SNAP K_s values of (a) 0, (b) -3 , and (c) -6 m^{-2} .

magnets and is cut by a vertical collimator placed between them. The beam halo is cut off, and the beam is kicked back by the downstream skew-sextupole magnets. Using this mechanism, the beam halo can be cut efficiently without the collimator heads being close to the beam core. An NLC is characterized by low impedance because the collimator head is not close to the beam core. Moreover, particles that are shifted horizontally have a weaker kick force in the vertical direction, as expressed by Eq. (5). Figure 2 shows the distortion of the vertical phase space when it is kicked by SNAP. As observed, the further the value of K_s from zero, the greater the position deviations of particles from zero.

The beam instability caused by the impedance of the collimator assumed here is transverse mode coupling instability (TMCI) and -1 mode instability [19,20] of single-bunch beam instability. TMCI is a well-known instability with the bunch current threshold expressed as follows (see Sec. 2.4.10 of [18]):

$$I b_{\text{TMCI}} = \frac{C_1 f_s E / e}{\sum k_{\perp,i} \beta_{y,i}}. \quad (6)$$

Here, $C_1 = 8$ denotes a constant value, f_s denotes the synchrotron frequency ($f_s = 2.13 \text{ kHz}$ for SuperKEKB LER), and E is the beam energy. The factor E/e represents the beam energy per unit charge, whose dimension is volt (V). The symbols $k_{\perp,i}$ and $\beta_{y,i}$ indicate the vertical kick

factor and β function, respectively, at the i th beam impedance source along the ring.

Herein, we denote the sum of the products of the vertical kick factor and the local vertical β function over all the vertical collimators as $\sum k_{\perp,i} \beta_{y,i}$.

Table II presents the design parameters of the SuperKEKB NLC. The collimator located between the SNAPs is designated D05V1. The vertical collimator structure of D05V1 has the same as those of D02V1 and D06V1 [21], as shown in Fig. 3 [22].

B. Items required for NLC

The major concern in NLC installations is the reduction of the dynamic aperture by the nonlinear magnetic fields of skew-sextupole magnets. This reduction results in a decrease in lifetime and injection efficiency. This limitation must be addressed in SuperKEKB, aiming for high current. Compared with other collimators, NLC for SuperKEKB must reduce BG without reducing the dynamic aperture and while maintaining extremely low impedance. To describe the collimator strategy in SuperKEKB, a schematic of the collimator location in SuperKEKB is shown in Fig. 4. As the LER has lower energy and higher bunch current, the impedance effect is considerable. Especially in the vertical collimators, the effect of impedance is significant.

From this point on, the vertical collimator in the LER installed with NLC will be described. In this figure, the IR

TABLE II. Design parameters of NLC at the SuperKEKB LER.

Parameters		Units	Values
Horizontal and vertical β functions at SNAP	$\beta_{x,ys}$	m	7.08/378.5
Horizontal and vertical β functions at D05V1	$\beta_{x,yc}$	m	3.55/4.05
Components of the transfer matrix from SNAP.1 to D05V1	R_{34}	m	37.2
Strength of SNAP	K_s	m^{-2}	-6.00

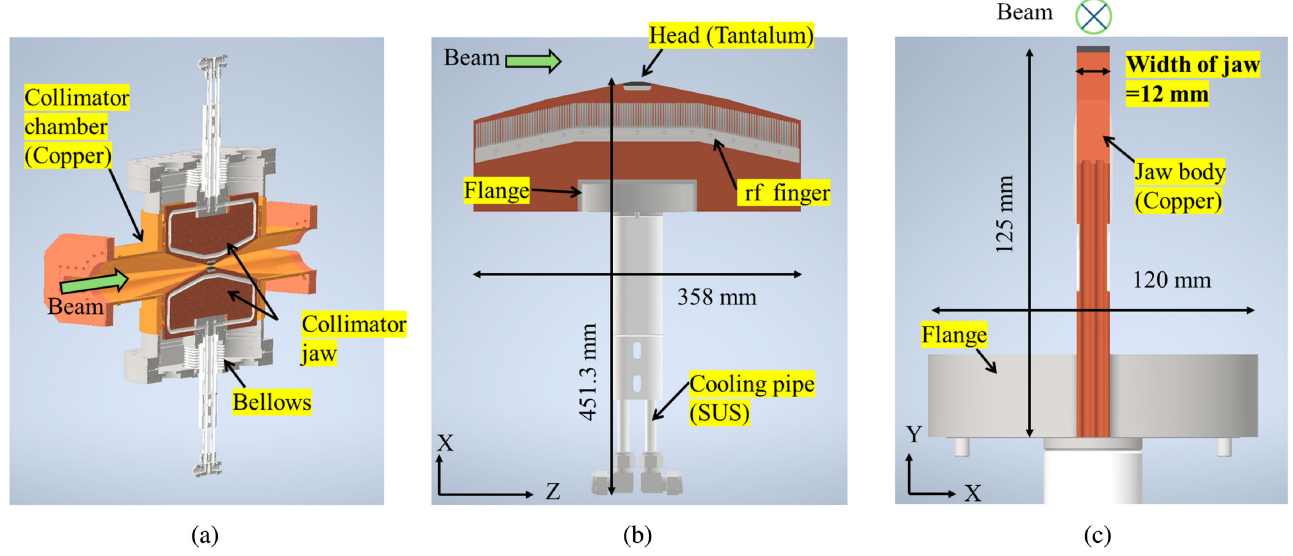


FIG. 3. Schematic drawing of the SuperKEKB-type vertical collimator with (a) overview of vertical YZ cross sections, jaws in (b) YZ planes, and (c) YX planes.

and XRM [23] refer to the interaction region and x-ray monitor for the measurement of the vertical beam size.

Table III lists the parameter values and half-gap (the distance from the beam to the collimator head) settings of the collimators used during the study for the case where $\beta_y^* = 1.0$ mm at the location of these four vertical collimators. QC1RP is the final focusing quadrupole magnet for the LER, located inside the final focusing superconducting quadrupole magnets (QCS) [24]. The QC1RP is characterized by the

largest vertical β function in the entire ring, and except for the collimators, it also has the smallest physical aperture. Because beam losses at QC1RP can significantly increase the background in the Belle II detector, in principle, the vertical collimator aperture must be set smaller than the aperture of QC1RP. The QC1RP aperture is listed in Table III to facilitate its direct comparison with the collimator aperture discussed in this paper. The vertical beam size depends on the bunch current and other operating conditions. Therefore, a representative vertical emittance of 20 pm, measured during the LER single-beam operation, is assumed to calculate the values listed in this table. The vertical aperture of D05V1 is calculated using the following equation:

$$A_{y,D05V1} = \frac{1}{2} R_{34} K_s y_s^2. \quad (7)$$

D06V1 closes the vertical aperture as narrowly as possible to cut off the beam tail of the injection beam and is the first to stop beams with abnormal orbits (termed the primary collimator). D02V1 is considered the most

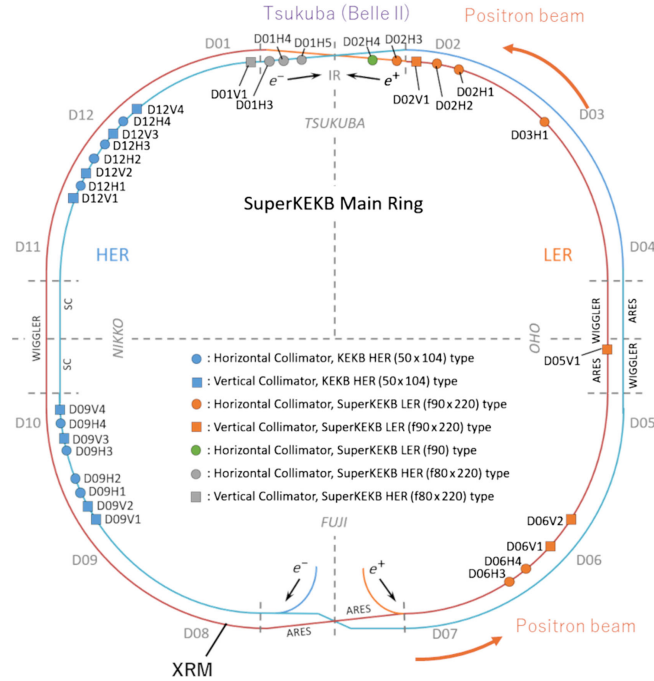


FIG. 4. Location of collimators in MRs. The notations H and V represent horizontal and vertical collimators, respectively.

TABLE III. Example of aperture on March 14, 2024. σ_y represents vertical beam size.

Collimators (magnet)	β_y (m)	Half-gap		$k_{\perp,i} \beta_{y,i}$ (10^{15} V/C)
		(mm)	$/\sigma_y$	
QC1RP	764.0	13.5	74.3	
D02V1	11.9	1.1	70.8	12.90
D06V2	20.6	1.8	88.7	10.66
D06V1	67.3	2.4	65.4	22.63
D05V1	4.05	(+ or -) 3.6	65.4 ^a	0.73

^aEffective collimation capability in units of σ_y .

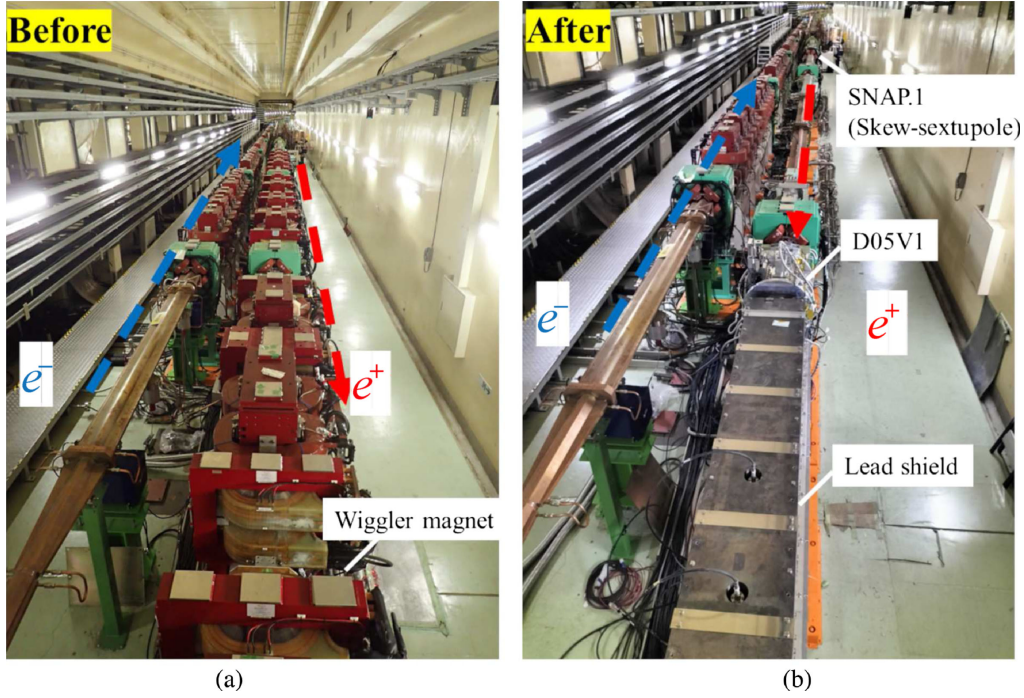


FIG. 5. Photograph of the “Oho” straight section (a) before NLC beamline change, where the wiggler magnets are installed, (b) after NLC beamline change.

important collimator in terms of operation because its damage would have a significant impact on the BG. Therefore, it requires more care than the primary collimator. D02V1 serves as the final defense for particle detectors and QCS, operating with the second narrowest aperture in the ring (termed the secondary collimator). D06V2 is installed as a backup in case D06V1 is damaged and to prevent particles scattered by D06V1 from reaching the IR. The D06V1, which is used as the primary collimator, has a high $k_{\perp,i}\beta_{y,i}$ value compared to other collimators, as shown in Table III. When impedance is high, beam instability becomes an issue during operation with higher bunch currents, making it difficult to use D06V1 in future operations. Therefore, we have required NLC to have low impedance and BG reduction capability equal to or greater than that of D06V1.

C. Construction of beamline for NLC

To realize NLC, part of the beamline in the “Oho” straight section was modified. Before constructing the NLC beamline, this section was a wiggler section. The wiggler magnets and wiggler beam pipes in this section were removed, and the skew-sextupole magnets and collimator were installed. Additionally, the configuration of the quadrupole magnets was also changed significantly. NLC was installed during the long shutdown 1 period from July 2022 to December 2023. The magnets and beam pipes were removed during the period from July to November 2022. Subsequently, the magnets and beam pipes were reinstalled and reconfigured during the period from December 2022 to September 2023. Following this activity, the maximum possible radiation shielding was

installed during the period from October to December 2023. Figure 5 shows photographs of the “Oho” straight section before and after the beamline modification for NLC installation.

III. MEASUREMENT RELATED TO NLC USING BEAMS

A. Measurement of optics for NLC

To investigate whether the beam is kicked as expected by SNAP, a bump was applied to the steering before SNAP.1, and the vertical beam position was measured using the beam position monitor (BPM) (MQN3OP, location outlined in red in Fig. 1) nearest to D05V1 when the beam was shifted vertically from the center of SNAP. The measurement (blue) and simulation (orange) are shown in Fig. 6. This simulation was performed using Strategic Accelerator Design software (SAD) [25]. The blue dotted line represents the measurement values fitted using a second-order polynomial. This figure indicates that the measured values generally follow a similar trend to the simulation. However, this figure indicates that the difference between simulation and measurement is greater when the kick angle is on the negative side. We suspect this may be due to an installation position error of the BPM.

B. Measurement of lifetime and injection efficiency when K_s is changed

The measurements of beam lifetime and injection efficiency described here were performed under the following

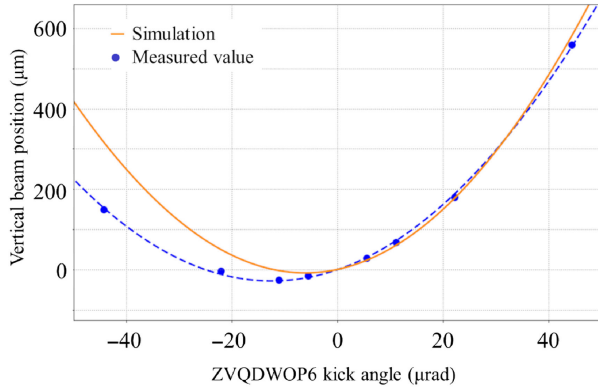


FIG. 6. Vertical beam position at MQN30P (BPM) nearest to D05V1 versus kick angle using vertical steering magnet.

conditions: LER single beam (no collision), $\beta_y^* = 1$ mm, and 94 bunches. Normally, operations are conducted with more than 2000 bunches. However, the measurement was performed using fewer bunches because, under high-current conditions during this study, beam loss in NLC section causes an increase in the number of radiation levels in the “Oho” experiment hall. Currently, efforts are underway to enhance radiation shielding at D05V1. As aforementioned, the concern with NLC is the reduction in dynamic aperture. We measured the beam lifetime and injection efficiency when the power supply to the skew-sextupole magnets was turned on and off. Figure 7 shows the beam lifetime divided by the square root of the vertical emittance when the power supply to the skew-sextupole magnets was turned on and off (on: $K_s = -6 \text{ m}^{-2}$, off: $K_s = 0 \text{ m}^{-2}$). This figure indicates that the beam lifetime when the power supply to the skew-sextupole magnets is turned on and off is

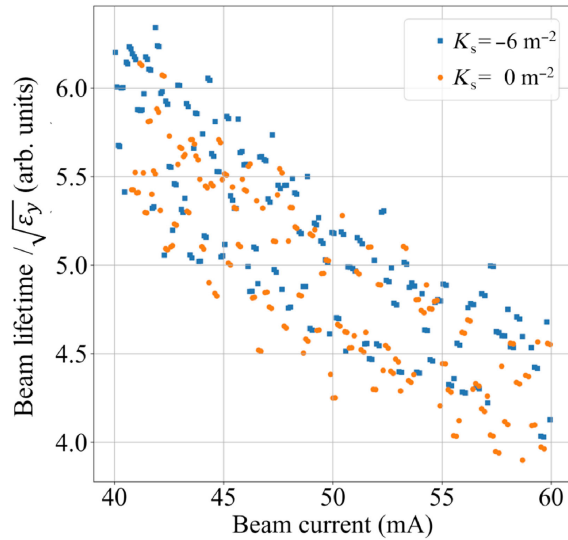


FIG. 7. Comparison of beam lifetime for different beam intensities when SNAP is turned on ($K_s = -6$) and off ($K_s = 0$). The vertical axis shows the measured beam lifetime divided by the square root of the vertical emittance.

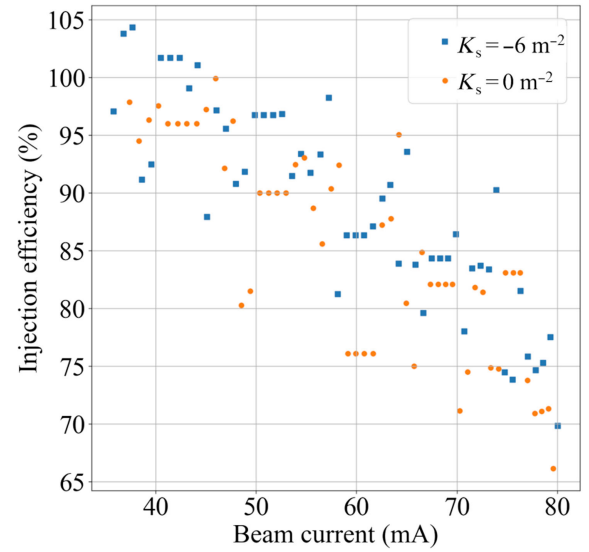


FIG. 8. Comparison of injection efficiency for different beam intensities when SNAP is turned on ($K_s = -6$) and off ($K_s = 0$).

almost the same. To compare apertures using the beam lifetime, the effect of the horizontal beam size should also be considered. However, since the horizontal beam size monitor was not available at the time of this measurement, only the vertical beam size was taken into consideration.

Figure 8 shows the injection efficiency in the cases of $K_s = 0 \text{ m}^{-2}$ and $K_s = -6 \text{ m}^{-2}$. Almost no difference in the injection efficiency is observed regardless of whether the skew-sextupole magnets for NLC are present or not. The definition of injection efficiency is the ratio of the increase in charge measured by the bunch current monitor within the ring to the charge measured by the BPM at the most downstream point of the beam transport line. During this measurement, calibration was not perfect, and some data show injection efficiency exceeding 100%.

Therefore, these measurement results show that the skew-sextupole magnets do not have a significant effect on the reduction of the dynamic aperture.

C. Demonstration of BG reduction effect by NLC

The primary contributors to BG in SuperKEKB are summarized as follows. The Touschek effect originates from interactions among particles within a single bunch, which exchange energy and thereby cause local variations in particle momentum. When these energy deviations occur in regions with nonzero dispersion, they give rise to horizontal oscillations. To suppress beam losses near the IR, horizontal collimators are strategically placed in the arc sections. Beam-gas Coulomb scattering arises from collisions between beam particles and residual gas atoms inside the beam pipe, leading to transverse motion of the particles. The most significant beam losses are observed around the QCS, where vertical oscillations dominate. Therefore, vertical collimators with narrow gaps are employed to

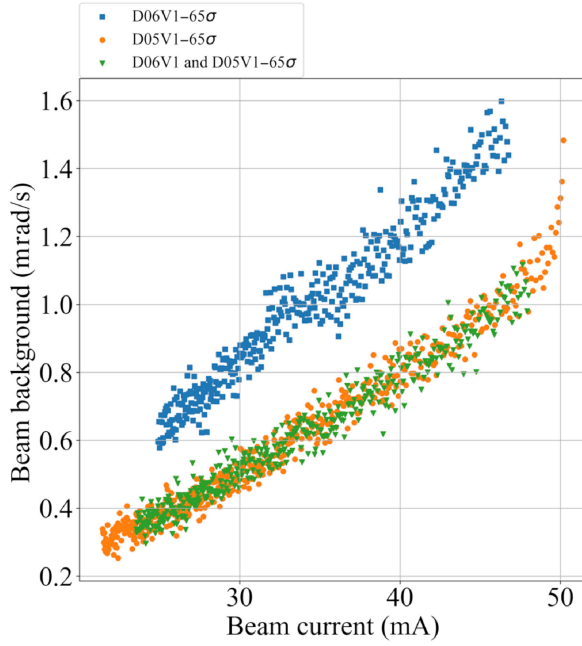


FIG. 9. Comparison of storage BG for different beam intensities when the vertical apertures between D06V1 and D05V1 are equal.

protect the QCS and the Belle II detector from excessive beam loss. During the current phase of SuperKEKB operation, such single-beam background processes are the predominant loss sources [26].

NLC was installed to enable the use of D05V1 instead of D06V1, which is the largest impedance source in the ring and is used as the primary collimator. Therefore, we investigated the aperture of D05V1 to verify whether its BG reduction capability is the same or higher than that of D06V1. SuperKEKB employs top-up injection during physics runs. Therefore, not only the storage BG but also the injection BG is a critical parameter for accumulating physics data. In this section, we describe storage BG and injection BG separately. The measured BG in this study was obtained from a diamond sensor installed near the interaction point. Details regarding the installation location of this measurement device are described in detail in Ref. [27].

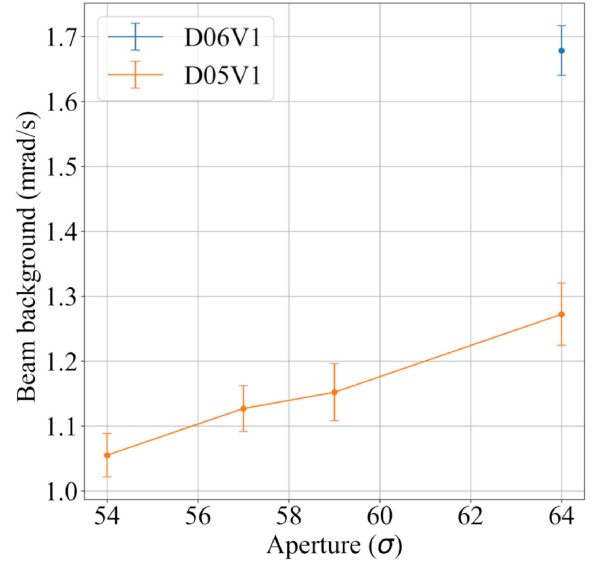


FIG. 10. Average storage BG as a function of aperture of the collimator, measured during a beam current decay from 50 to 30 mA. The vertical axis shows the mean BG level, and the horizontal axis represents the aperture of the collimator.

Initially, the storage BG reduction capabilities are discussed. Figure 9 shows the measurement results for storage BG. The vertical aperture of D05V1 is the value derived using Eq. (7). The vertical aperture of D06V1 is the half-gap divided by the vertical beam size. This figure plots the decay data to examine only the storage BG, illustrating that D05V1 has a higher storage BG reduction capability than D06V1 with the same aperture. This is due to D05V1 being located closer to the interaction point, which enables it to more efficiently mitigate single-turn losses arising from Coulomb scattering. The collimator settings during measurement shown in Fig. 9 are listed in the Table IV, where only the half-gaps of D06V1 and D05V1 differ, whereas those of D06V2 and D02V1 remain unchanged; this difference has been introduced herein solely to compare the effects of D06V1 and D05V1.

Figure 10 shows the measurement results for storage BG. As shown, as the aperture of D05V1 narrows, the storage

TABLE IV. Collimator settings for storage BG measurement.

Setting name	D06V1 half-gap/ σ $k_{\perp,i}\beta_{y,i}$	D06V2 half-gap/ σ $k_{\perp,i}\beta_{y,i}$ (10^{15} V/C)	D05V1 half-gap/ σ $k_{\perp,i}\beta_{y,i}$ (10^{15} V/C)	D02V1 half-gap/ σ $k_{\perp,i}\beta_{y,i}$ (10^{15} V/C)
D06V1-65 σ	2.4 (mm)/65.4 σ 22.6×10^{15} (V/C)	1.8 (mm)/88.7 σ 10.6×10^{15} (V/C)	14.0 (mm)/128.7 σ 0.1×10^{15} (V/C)	1.1 (mm)/71.3 σ 12.8×10^{15} (V/C)
D05V1-65 σ	8.0 (mm)/218.0 σ 3.7×10^{15} (V/C)	1.8 (mm)/88.7 σ 10.6×10^{15} (V/C)	3.6 (mm)/65.4 σ 0.7×10^{15} (V/C)	1.1 (mm)/71.3 σ 12.8×10^{15} (V/C)
D06V1 and D05V1-65 σ	2.4 (mm)/65.4 σ 22.6×10^{15} (V/C)	1.8 (mm)/88.7 σ 10.6×10^{15} (V/C)	3.6 (mm)/65.4 σ 0.7×10^{15} (V/C)	1.1 (mm)/71.3 σ 12.8×10^{15} (V/C)

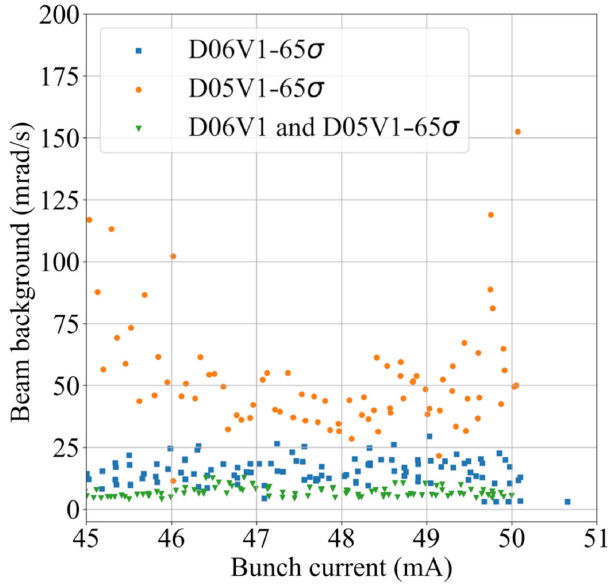


FIG. 11. Comparison of injection BG when the vertical apertures of D06V1 and D05V1 are equal. This graph does not show values below 2 mrad/s because the storage BG reduces the visibility of the plot.

BG decreases. Moreover, D05V1 has a higher storage BG reduction capability than D06V1 with the same aperture.

Next, we describe the injection BG reduction capability of NLC. We discuss the injection BG reduction capability of NLC separately from its storage BG reduction capability because the ability of NLC to cut the injection beam halo differs from that of a normal collimator owing to the relationship between the injection oscillation and the kick force induced by the skew-sextupole magnet. As the current injection method of SuperKEKB LER is an off-axis injection, the injection beam oscillates horizontally around the storage beam. The reason the vertical collimator can cut the injection BG in the SuperKEKB LER is the large size of the injection beam and its vertical oscillation due to X-Y coupling in the ring. For horizontal oscillation, such as an injection beam, Eq. (3) indicates that the vertical kick force Δp_y from SNAP decreases. From Eq. (3), it can be seen that when x is large (including the injection beam) the beam halo can, in principle, be cut by the collimator jaw opposite to the one that cuts the storage BG. However, in practice, due to the relatively small β_x at SNAP, it is not possible to cut the BG using the opposite collimator jaw.

For D05V1 to reduce the injection BG to the same level as D06V1, the aperture of D05V1 should be made narrower than that of D06V1. Figures 11 and 12 show the measurement results for injection BG. Figure 11 shows the beam current on the horizontal axis and the injection BG on the vertical axis. Figure 11 shows the vertical aperture of the collimator on the horizontal axis and the injection BG on the vertical axis. These figures show that D05V1 cannot reduce the injection BG to a greater extent than D06V1.

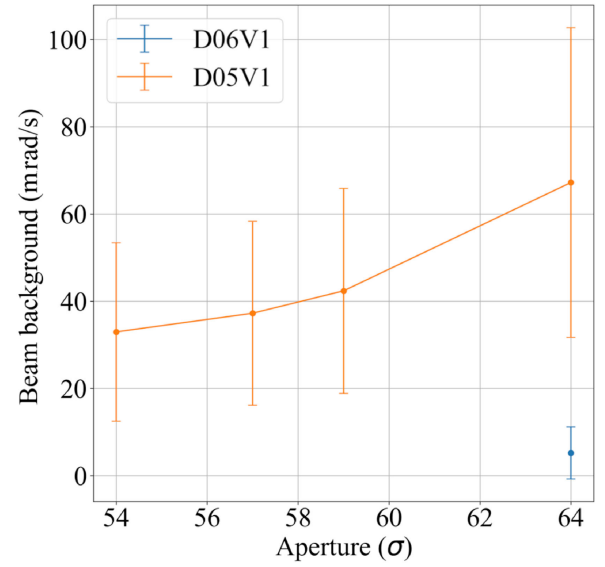


FIG. 12. Average injection BG as a function of aperture of the collimator, measured during a beam current increasing from 30 to 50 mA.

Figure 13 shows the half-gap of D05V1 that provides the same collimation capability as that of D06V1 for the storage BG (orange line) and for the injection BG with the several values of β_x at SNAP (red line, in case of $\beta_x = 7$ m at SNAP) as the function of the half-gap of D06V1.

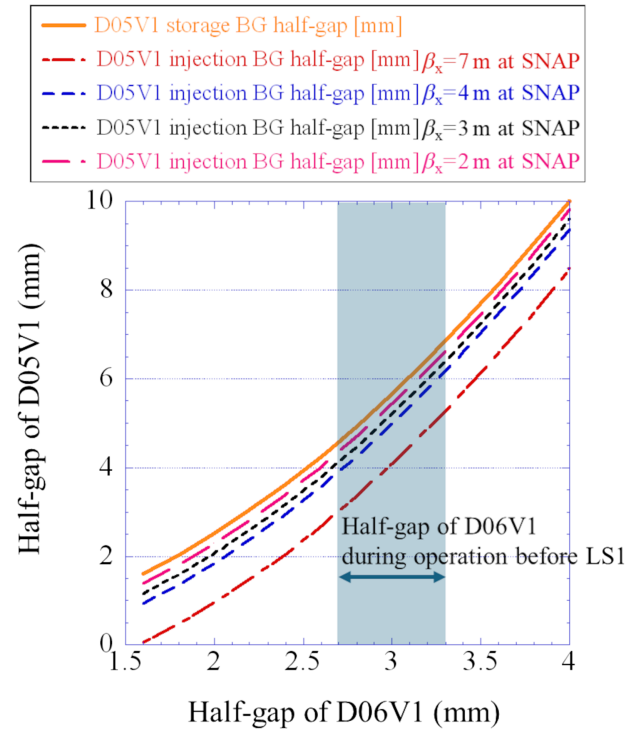


FIG. 13. Half-gap of D05V1 versus half-gap of D06V1. Changes in half-gap of D05V1 considering the effects of injection oscillation when changing β_x at SNAP.

Figure 13 shows the half-gaps of D06V1 and D05V1 on the horizontal and vertical axes, respectively. This calculation was performed using the injection oscillation measurement results of $2J_x = 2 \times 10^{-6}$ m. Here, the injection amplitude is the center-of-mass of the beam (1.13×10^{-6} m) plus 3σ of the horizontal beam size of the injection beam (0.836×10^{-6} m). The size of the injection beam is based on past measurements [28]. Figure 13 shows that when the half-gap of D06V1 is 2.4 mm, setting the half-gap of D05V1 to 3.8 mm for storage BG and 2 mm for injection BG (when $\beta_x = 7$ m at SNAP) can improve its BG reduction capability similar to that of D06V1. Figure 13 shows that as β_x at SNAP decreases, the curve that cuts the injection BG approaches that which cuts the storage BG. However, the $\beta_{x,s}$ and $\beta_{x,c}$ are negatively correlated. Therefore, when the $\beta_{x,s}$ is squeezed, the horizontal maximum amplitude of injection beam at D05V1 ($\text{MAX amp}_{x,c}$) can be roughly expressed by the following equation:

$$\text{MAX amp}_{x,c} \propto \sqrt{\frac{(2J_x)}{\beta_{x,s}}}. \quad (8)$$

In other words, the lower limit of $\beta_{x,s}$ is determined by the range in which the injection amplitude in D05V1 does not exceed the horizontal width (12 mm) of the collimator jaw. The structure of the collimator jaw is shown in Fig. 3. Figure 14 plots the calculation results of Eq. (8). Figure 14 shows $\beta_{x,s}$ on the horizontal axis and the horizontal amplitude at D05V1 on the vertical axis. This figure reveals that $\beta_{x,s}$ must be greater than approximately 1.4 m for the maximum amplitude of the injection beam to exceed the width of the collimator jaw. During 2024c, when operating with β_x at SNAP set to 3 m, the injection BG was cut as

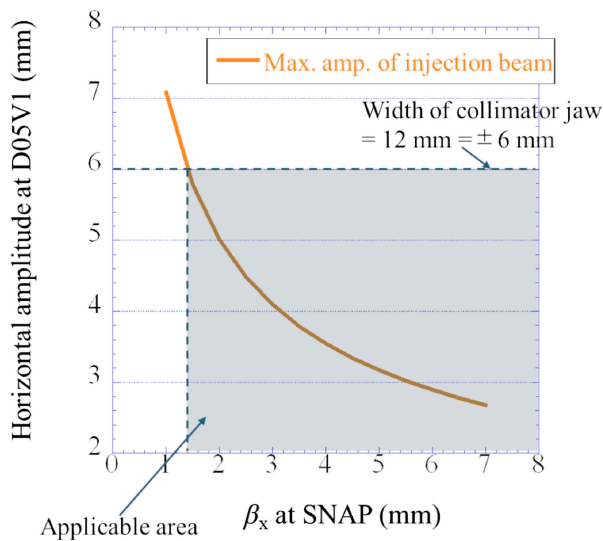


FIG. 14. Injection oscillation at D05V1 versus β_x at SNAP.

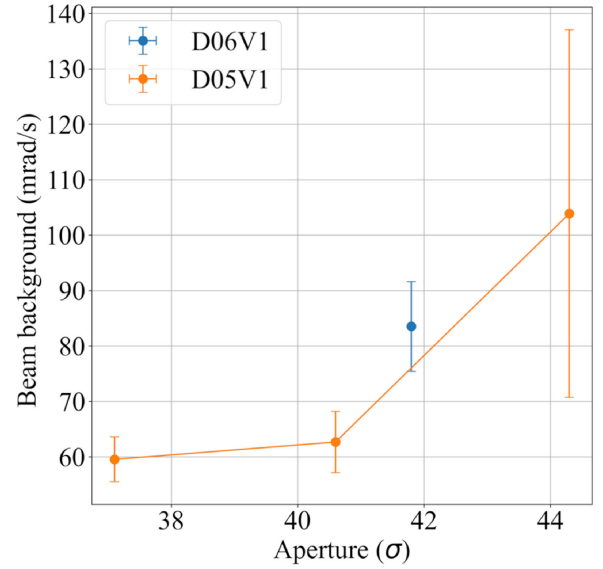


FIG. 15. BG including injection timing versus the vertical aperture. Vertical aperture of D05V1 considers the effects of injection amplitude. At the time of measurement, β_x at SNAP is 3 m.

expected. Figure 15 shows a vertical aperture considering injection amplitude on the horizontal axis and BG on the vertical axis. The number of bunches at this time of measurement was 2346, and the beam current was 300 mA. This measurement result was obtained during a physics run, not during beam studies, and is less certain than those from beam studies. Since a study to determine the optimal value for this parameter has not yet been conducted, it will be necessary to confirm this in future beam studies.

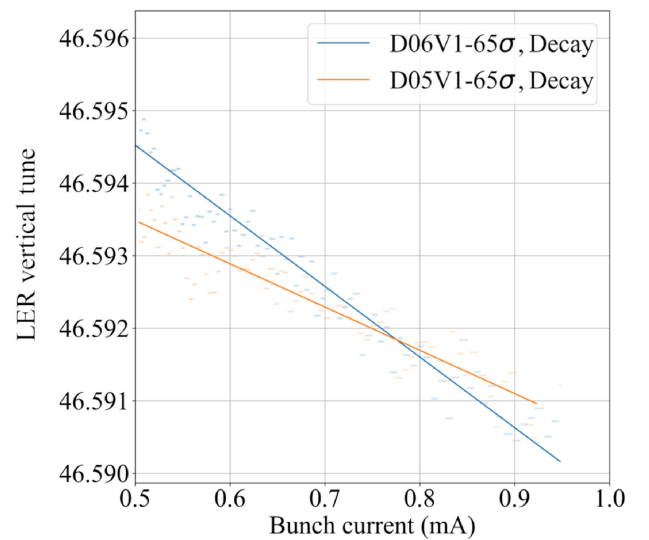


FIG. 16. Comparison of LER vertical tune shift measurements for equal vertical apertures of D06V1 and D05V1.

TABLE V. Measured and calculated value of LER vertical tune shift.

Collimator setting	Measured $\Delta\nu_y$ (/mA)	Calculated $\Delta\nu_y$ (/mA)
D06V1-65 σ	0.0097	0.0092
D05V1-65 σ	0.0059	0.0055

D. Evaluation of impedance reduction by NLC

In the SuperKEKB LER, a vertical beam size blowup was observed during the high bunch current study. This phenomenon was caused by the -1 mode instability (interaction between beam impedance and the bunch-by-bunch feedback system) [19]. When operating at

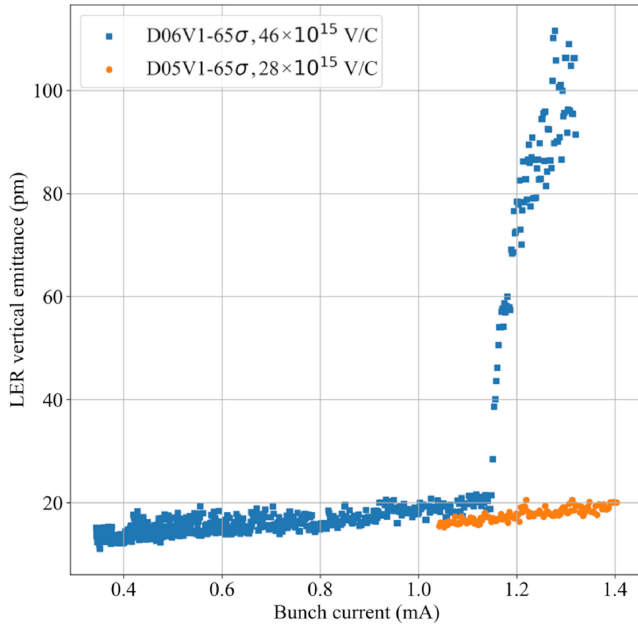


FIG. 17. Comparison of the bunch current threshold for the occurrence of the vertical beam size blowup for equal vertical apertures of D06V1 and D05V1.

$\beta_y^* = 1$ mm, the bunch current threshold for the occurrence of the vertical beam size blowup was approximately 1.2 mA [29]. As this value is lower than the design bunch current (1.4 mA), the impedance should be reduced and operational issues caused by beam impedance should be eliminated. We measured the tune shift to verify the possibility of reducing impedance using D05V1 rather than D06V1. The bunch current threshold for the occurrence of the vertical beam size blowup was investigated. The results of the vertical tune shift measurement are shown in Fig. 16 and Table V. The theoretical values were calculated using the kick factor obtained assuming a bunch length of 6 mm using the following equation [30]:

$$\Delta\nu_y = \frac{T_0 I_b}{4\pi E/e} \sum k_{\perp,i} \beta_{y,i}. \quad (9)$$

Here, T_0 is revolution time, and I_b represents the bunch current. This figure and table indicate that the calculated and measured values are extremely close and that using D05V1 results in a smaller tune shift slope. The kick factor was calculated using GdfidL [31]. The collimator settings used during these impedance measurements are the same as those shown in Table IV.

The measurement results of the occurrence of the vertical beam size blowup are shown in Fig. 17. The bunch current is represented on the horizontal axis and the vertical emittance on the vertical axis. This figure reveals that when D05V1 is used, the vertical beam size blowup does not occur even at the design bunch current (1.4 mA); however, when D06V1 is used, the vertical beam size blowup occurs sharply from a bunch current of approximately 1.2 mA. Figure 18 shows the vertical tune spectrum of the pilot bunch without D05V1 (blue plot), as shown in Fig. 17. This figure indicates that when the bunch current is high (1.25 mA), synchrotron sideband peak is higher in the tune spectrum. In such cases, the beam becomes unstable and BG often increases.

The measurement results of the tune shift and the observation of the vertical beam size blowups reveal the

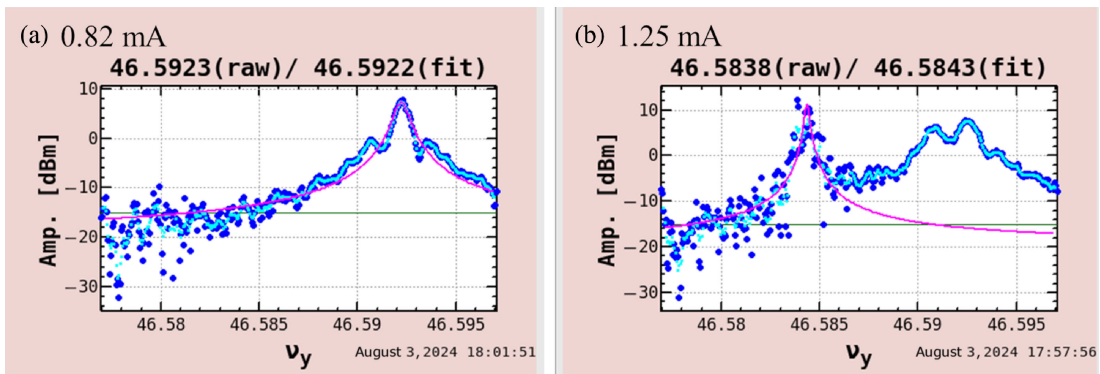


FIG. 18. Vertical tune (ν_y) spectra of the pilot bunch in LER at the bunch current = 0.82 mA (a) and 1.25 mA (b).

possibility of reducing the impedance and raising the bunch current threshold for the occurrence of the vertical beam size blowups using D05V1 rather than D06V1, as expected.

IV. SUMMARY

SuperKEKB is a new-generation electron-positron collider designed to achieve ultrahigh luminosity for exploring physics beyond the Standard Model. During the 2024ab run, the machine demonstrated world-leading performance, but operational challenges related to beam collimation were identified.

To address these issues, SuperKEKB installed an NLC in the LER, marking the first implementation of such a system, to the best of our knowledge. The beamline for NLC was constructed between July 2022 and November 2023. NLC utilizes a pair of skew-sextupole magnets (SNAP) connected via a $-I'$ transfer matrix to cancel geometric aberrations. This configuration allows the beam halo to be cut without placing collimator heads near the beam core, significantly reducing impedance.

A major concern in NLC design is the preservation of dynamic aperture, which affects beam lifetime and injection efficiency. Measurements confirmed that activating SNAP did not degrade these parameters.

The effectiveness of NLC was evaluated by comparing the BG reduction capabilities of the newly installed D05V1 collimator with the conventional D06V1, which has the highest impedance in the ring. Storage BG measurements using diamond sensors near the interaction point showed that D05V1 achieved equal or better BG reduction than D06V1. For injection BG, D05V1 required a narrower aperture to match the performance of D06V1 because of reduced vertical kick during horizontal injection oscillations. Trial tuning revealed that reducing β_x at SNAP from 7 m to approximately 3 m enables D05V1 to effectively suppress injection BG without exceeding the physical limits of the collimator jaw.

Impedance reduction was demonstrated through tune shift measurements and vertical beam size blow-up investigations. When D05V1 replaced D06V1, the bunch current threshold for the vertical beam size blowup increased from 1.2 mA to beyond the design value of 1.4 mA, confirming improved beam stability. Theoretical and measured tune shifts were consistent.

In summary, NLC successfully reduced both BG and impedance while preserving dynamic aperture. These results validate the nonlinear collimation concept and offer a promising approach for future high-luminosity colliders.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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