

Investigation of sudden beam loss at SuperKEKB

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In SuperKEKB, mitigation of sudden beam losses (SBLs) is essential to improve the luminosity. SBL refers to the rapid loss of a substantial portion of the stored beam current within a few revolutions. During SuperKEKB operation from 2019 to 2024, over 200 SBL events were observed, in which a beam abort with 5%–40% beam loss occurred within 2–3 turns, making high beam current operation difficult. The frequency of SBLs was very high, especially in the low-energy ring (LER). The occurrence of SBLs was highly concentrated during beam-current upgrade phases, presenting a severe operational bottleneck. While SBLs were rare during stable operations at lower currents, the frequency escalated to more than five events per day when operating at higher beam currents. These frequent events triggered intense beam losses, resulting in 11 quenches of the final-focus superconducting quadrupole magnets (QCS) within a period of less than three weeks in December 2024. Furthermore, SBL events could damage the collimator heads and the Belle II detector, causing devastating impacts on operation. SBLs occurred under both noncollisional and collisional conditions, but only under circumstances involving a small beam size at the interaction point and a high beam current. Most SBL events were accompanied by vacuum pressure bursts, primarily in the wiggler section of the LER, and an increase in beam size was also observed during these events. To investigate this phenomenon, SBL was artificially reproduced during beam operation and subsequently discharging the clearing electrodes. Inspecting the wiggler beam pipe, we found black stains, and removal of these stains led to a significant reduction in the frequency of SBLs. The black stains we discovered were identified as degraded vacuum sealant through observations using synchrotron radiation. This paper reports the results of an artificial reproduction test of the SBL phenomenon (knocking on the beam pipe, discharge inside the beam pipe), and an investigation of these black stains, including their composition and formation mechanism.

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I. INTRODUCTION

SuperKEKB is an electron-positron collider designed to achieve luminosity performance significantly higher than those attained by its predecessor, KEKB. This increase enables the investigation of phenomena beyond the standard model [1]. The SuperKEKB main ring (MR) comprises two storage rings: a high-energy ring (HER) for a 7 GeV electron beam and a low-energy ring (LER) for a 4 GeV positron beam [2]. During the upgrade from KEKB to SuperKEKB, new beam pipes were installed in 93% of the LER and 18% of the HER [3]. The new HER beam pipes are mainly located upstream and downstream of the

interaction point (IP), including the local chromaticity correction region. The layout of the SuperKEKB MR is shown in Fig. 1.

Figure 1 illustrates the schematic locations of the collimators and wiggler sections in the LER. In this diagram, IR refers to the interaction region [4], BOR represents the bunch oscillation recorder [5], and SRM denotes the synchrotron radiation monitor [6]. The SuperKEKB MR is a large storage ring with a circumference of approximately 3 km. Twelve auxiliary rooms, labeled D01–D12, are distributed along the ring at regular intervals. The boundary between D01 and D02 corresponds to the IP, with D02 located upstream of the IP for the LER and D01 upstream for the HER, as the positrons circulate counter-clockwise. The LER wiggler sections are positioned at D04, D10, and D11.

To achieve high luminosity, SuperKEKB employs a nano-beam scheme to minimize the vertical beam size at the IP [2]. This approach increases the beam background (BG) inside the Belle II detector [1], primarily due to the

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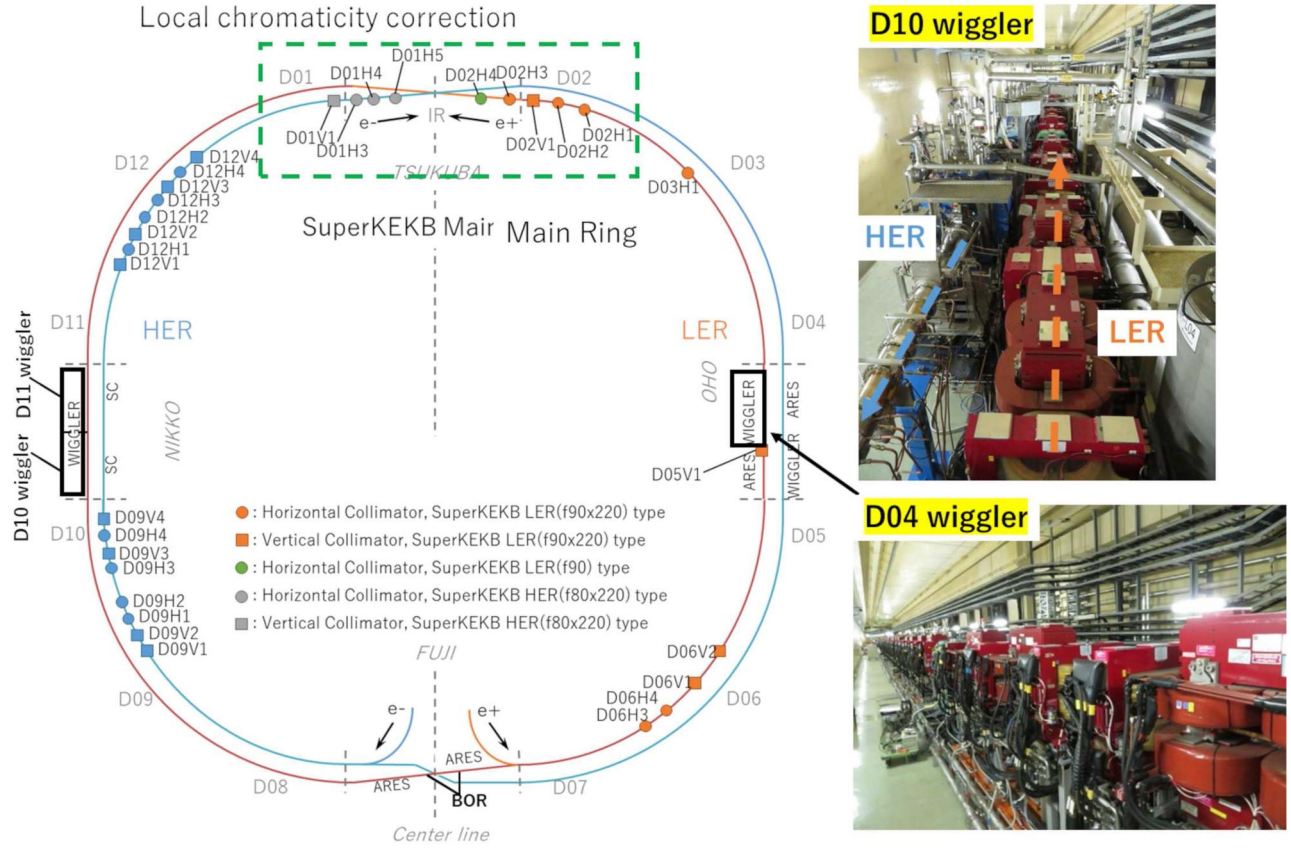


FIG. 1. Layout of the SuperKEKB main ring. The location of collimators and wiggler sections in the LER is displayed. H and V in the collimator labels denote the horizontal and vertical collimators, respectively.

large vertical β function in the final-focus superconducting quadrupole magnets (QCS) [7]. The large vertical β function at the QCS compress the beam for the IP and raises the probability of beam loss in this region. To date, SuperKEKB has achieved a minimum vertical beta function at the IP, β_y^* , of 0.8 mm [8], which is the smallest value ever realized in any operational production-type accelerator worldwide.

Table I summarizes the target design specifications and the actual performance recorded on the last day of the 2024 c run (October 9–December 27, 2024). SuperKEKB

achieved its unprecedented luminosity records only after implementing the crab-waist collision scheme [9], the first experimental test of which was successfully demonstrated in 2010 [10]. Although SuperKEKB has surpassed the peak luminosity of KEKB by more than a factor of two, a major obstacle to further luminosity enhancement remains: the frequent occurrence of sudden beam loss (SBL) events [11].

In this study, we present a comprehensive investigation of the SBL phenomenon at SuperKEKB, which has remained unresolved for nearly 5 years. Section II reviews

TABLE I. Design parameters and the parameters reached on the last day of the 2024 c run at SuperKEKB. The bunch length is not routinely measured during physics run; therefore, the corresponding values for the 2024 c run are not listed.

Parameters	Units	Design		2024c run last day	
		LER	HER	LER	HER
Beam currents	A	3.6	2.6	1.63	1.25
Energy	GeV	4.0	7.0	4.0	7.0
Number of bunches		2500		2346	
Bunch length	mm	6	5		
β_x^*/β_y^*	mm	32/0.27	25/0.30	60/1.00	60/1.00
Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	8×10^{35}		5.1×10^{34}	

the characteristics and operational impacts of SBL events. Section III describes beam-based reproduction experiments and mitigation efforts. Section IV reports laboratory studies on the black stains and their properties. Finally, Sec. V summarizes the key findings of this study.

II. OVERVIEW OF SUDDEN BEAM LOSS

A. Phenomena observed during sudden beam loss

SBL events have been observed in both the LER and HER at SuperKEKB. Notably, such events were never reported in the HER during the KEKB era, despite the beam pipe configuration in the HER remaining largely unchanged between KEKB and SuperKEKB [3]. This observation suggests that the occurrence of SBL may be linked to operational conditions unique to SuperKEKB, or that the extensive reconfiguration of the IR, including newly introduced IR hardware components, could be a primary or major contributing factor. Alternatively, the SBL phenomenon may not stem from a single cause but rather from a combination of both these unique operational conditions and potential IR hardware influences.

At SuperKEKB, SBL events are significantly more frequent in the LER and tend to cause more severe consequences for the Belle II detector. For instance, during the 2024ab run (January 29–July 1, 2024), a total of 144 SBL events were recorded in the LER, compared with only 19 events in the HER. In most cases, SBL occurs only when the beam current exceeds approximately 500 mA,

indicating a strong dependence on the stored beam intensity.

Although SuperKEKB operates as a collider, SBL occurs regardless of whether the beams are colliding. This observation clearly demonstrates that SBL is unrelated to beam-beam interactions. Furthermore, no SBL events were observed during high-current operations at KEKB, nor during Phase-1 operation of SuperKEKB (February 1–June 28, 2016), even when the beam current exceeded 500 mA. During Phase-1, the QCS magnets—essential for implementing the nano-beam scheme—were not installed, and the nano-beam optics were therefore not applied. Collectively, these observations strongly suggest that SBL arises only under conditions in which both (i) the nano-beam scheme is employed, resulting in an extremely small vertical beam size at the IP, and (ii) the stored beam current is high.

1. Beam orbit variation during sudden beam loss

Figure 2 shows a typical example of bunch-by-bunch beam orbit variation and the corresponding loss signals recorded by the BOR during an SBL event. The data show that a slight horizontal displacement of the beam orbit occurred one revolution before the onset of beam loss. Considering that one revolution in the SuperKEKB main ring takes only 10 μ s, this observation indicates that the center-of-mass of the beam shifts on an extremely short timescale followed by catastrophic beam loss.

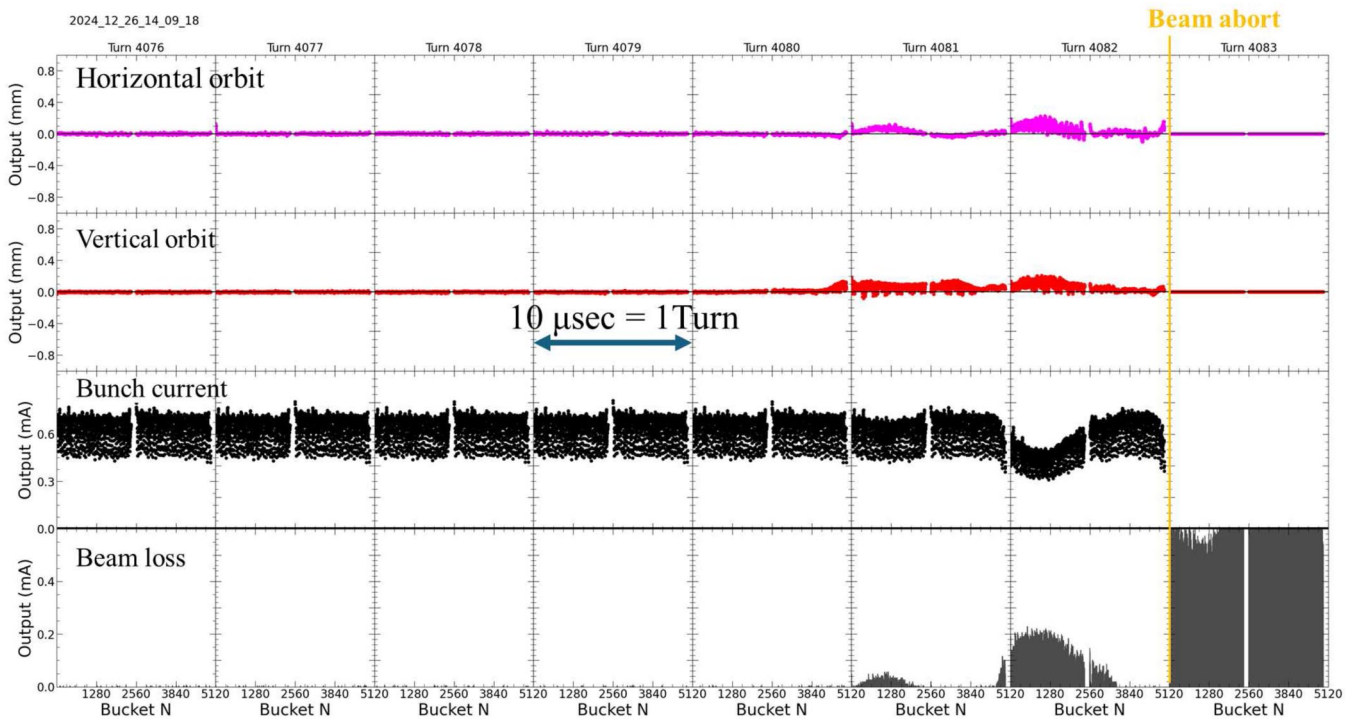


FIG. 2. Example of bunch-by-bunch beam orbit variation and beam loss at SBL event.

Although rapid beam loss phenomena have also been observed in other colliders such as Hadron-electron ring accelerator [12] and the Large Hadron Collider [13], the recorded loss rates in those machines are several orders of magnitude slower than those observed at SuperKEKB. This discrepancy might partly stem from differences in the sensitivity or temporal resolution of the diagnostic equipment at each facility; however, regarding such an extremely short timescale as observed at SuperKEKB, to the best of our knowledge, the only comparable phenomenon documented in the literature is that observed in the PEP-II LER [14]. The scarcity of fully comparable cases underscores the uniqueness and complexity of SBL at SuperKEKB.

2. Beam size observed during SBL events

A rapid increase in the vertical beam size was frequently observed during the final revolution immediately preceding an SBL event. Figure 3(a) shows the beam size measured at the moment of the SBL, illustrating this characteristic enlargement. For comparison, Fig. 3(b) shows the beam size observed during a manual beam abort performed as part of optical adjustment procedures. This comparison highlights the clear difference between ordinary beam aborts and aborts associated with SBL events. Details of the beam size measurement method are provided in Ref. [15].

As shown in Fig. 2, the center-of-mass position of the beam does not exhibit a significant shift during SBL events. This observation suggests that the abrupt increase in the vertical beam size, rather than a large orbit displacement, played a dominant role in triggering the sudden loss of the stored beam. Therefore, the onset of SBL can be plausibly associated with this rapid beam-size growth.

3. Pressure burst phenomenon observed simultaneously with SBL

In most LER cases, pressure bursts were observed simultaneously with SBL events. A typical example is presented in Fig. 4. These bursts occurred predominantly in the wiggler sections of the LER, although other locations such as the interaction region (IR) and collimators also exhibited frequent bursts. Figure 5 shows the distribution of pressure bursts detected during SBL events in the LER during the 2024ab run, illustrating that the majority were concentrated in the wiggler sections. In contrast, for the HER cases, pressure bursts were not

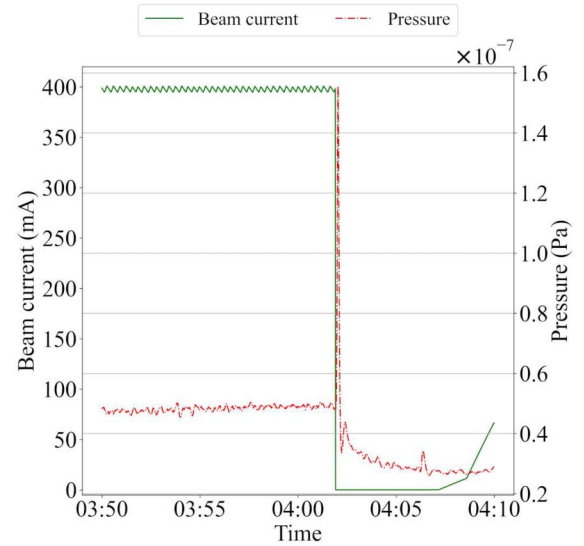


FIG. 4. A typical example of a pressure burst measured during an SBL event. The pressure burst occurs almost simultaneously with the beam abort.

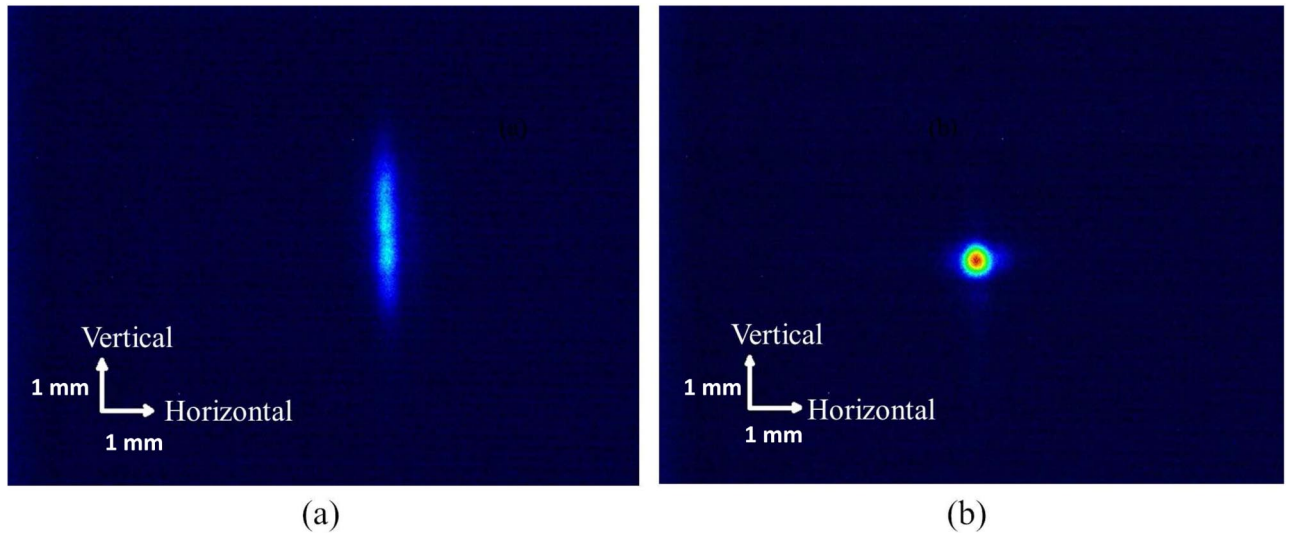


FIG. 3. Images captured by a gated camera during the final turn before beam abort. Exposure time: 100 ns. (a) Beam size observed during an SBL event. (b) Beam size observed when a beam abort was manually performed.

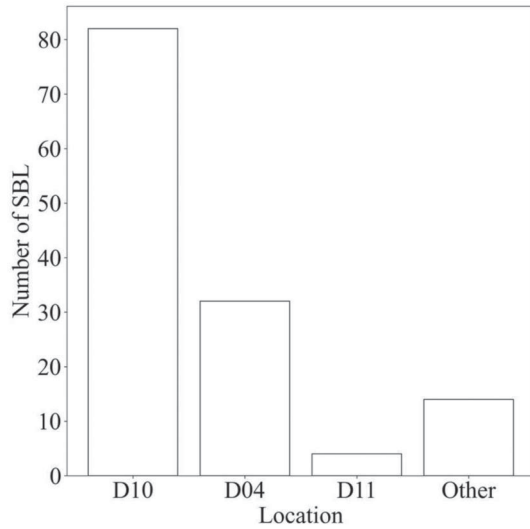


FIG. 5. Distribution of SBL events across locations where pressure bursts were detected during the 2024ab run.

detected in the majority of the SBL events; specifically, approximately 76.3% of the events recorded during the 2024 run showed no significant pressure bursts. Furthermore, the remaining sparse events showed no dominant localized concentration. This distinct lack of simultaneous pressure bursts inherent to the HER makes it highly challenging to identify specific problematic locations or source zones responsible for sudden beam losses (SBLs) in this ring.

Regarding the spatial distribution of the pressure bursts, the localization resolution is determined by the configuration of the vacuum system instrumentation. Approximately 300 vacuum gauges are distributed along the 3-km circumference of the LER, maintaining an average longitudinal spacing of roughly 10 m. When a substantial pressure burst occurs, multiple adjacent gauges can simultaneously detect the pressure rise, which occasionally allows for an estimation of the event location. However, due to the discrete positions of the gauges and the complex pressure gradients influenced by nearby pumping locations, the precise longitudinal position of a pressure burst cannot always be uniquely identified.

Before dedicated beam studies were conducted during the 2024ab and 2024 c runs, the causal relationship between pressure bursts and SBL was unclear. Specifically, it was uncertain whether pressure bursts caused SBL or whether beam behavior associated with SBL triggered the pressure bursts. Further details of these investigations are provided in Sec. III.

B. Impacts of sudden beam loss on SuperKEKB operation and Belle II

SBL events caused damage to both collimator heads and the Belle II detector, and it hence had a serious impact on the accelerator operation. Figure 6 shows a tantalum

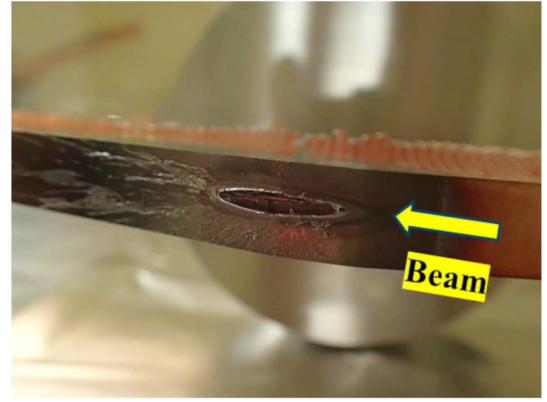


FIG. 6. A collimator jaw exhibiting surface damage attributed to impact of beam losses during an SBL event.

collimator head exhibiting gouged areas and spiky protrusions, with more severe damage appearing on the downstream side of the beam direction. In particular, damage to the vertical collimator near the IP increases the BG. A rapid rise in the BG caused by collimator damage occasionally necessitates the suspension of accelerator operations and the replacement of the affected jaw [16]. However, following such replacement, the vacuum pressure near the collimator often deteriorates, requiring a narrower collimator aperture, which in turn increases the likelihood of further damage.

The most critical consequence of SBL events is the damage inflicted on the sensors in the Belle II detector. Figure 7 shows an example of the radiation dose recorded by the diamond sensors during an SBL event, indicating that a substantial dose is delivered to the components [17]. The labels in the figure, such as BP_FW_35, denote the locations of the loss monitors around the beam pipe (BP) at the interaction point; “FW” and “BW” represent the forward and backward directions, respectively, and the

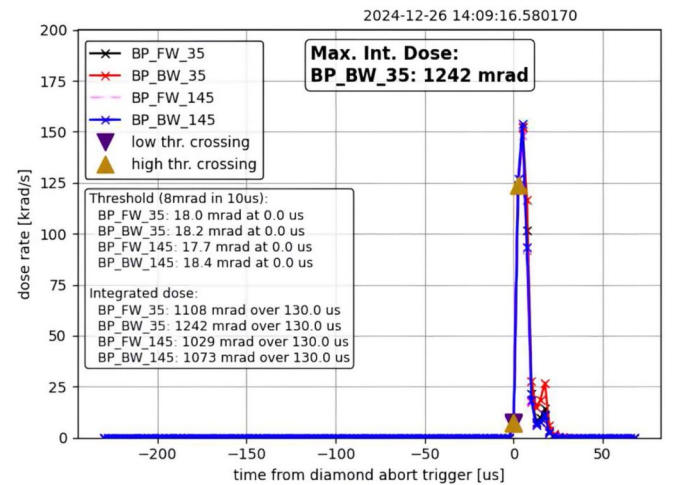


FIG. 7. Dose received by sensors in Belle II during an SBL event on December 26, 2024.

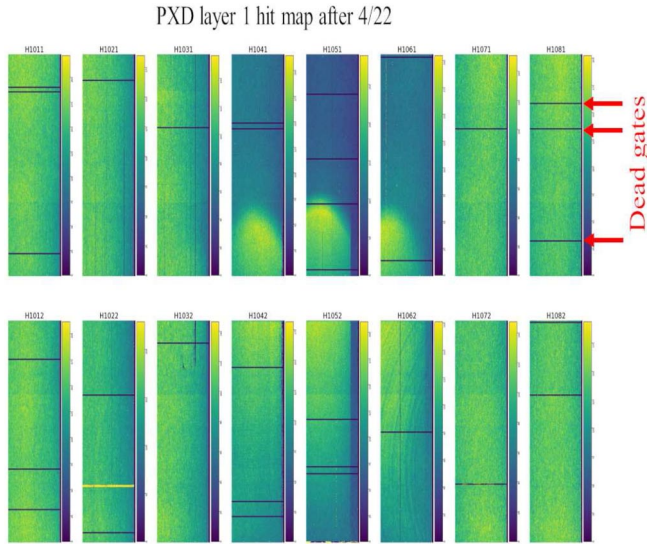


FIG. 8. Damage to the pixel detector (PXD) gate resulting from an SBL event on April 22, 2024.

numbers indicate the azimuthal angles in degrees, with 90° defined at the top (ceiling) side. Further details of the sensor layout are available in Ref. [17].

While the specific event shown in Fig. 7 resulted in collimator damage and a quench of the QCS magnets, it is distinct from the events that directly damaged the pixel detector (PXD) [18,19]. During the SBL events that actually caused PXD damage, the radiation dose exceeded the measurement limits of the diamond sensors, causing them to saturate. Consequently, the exact quantitative dose corresponding to the PXD damage limit remains unidentified.

During Long Shutdown 1 (July 2022–January 2024), the PXD was replaced with a fully equipped 20-ladder system. However, nearly 2% of the gates became inoperable due to SBL events on April 22 and May 6, 2024. Figure 8 illustrates damage to the PXD gates, with the blue horizontal line indicating the section containing dead gates.

To prevent further damage, physics runs are currently conducted with the PXD power supply turned off until the risk of additional SBL-induced damage is mitigated.

III. INVESTIGATION PERFORMED DURING BEAM OPERATION

SBL events have been detected at SuperKEKB since Phase-2 (March 19–July 17, 2018) operation. However, until the 2024ab run, several proposed mechanisms had not been confirmed through direct beam-based experimentation. Because SBL events in the LER were more frequent and damaging to Belle II, the beam studies for SBL were almost entirely conducted at the LER. Therefore, the remainder of this discussion concentrates on the LER.

A. Knocker study and discharge study

The beam pipes in the wiggler section were aligned during a maintenance day in the 2024ab run. This study was not intended to investigate the cause of SBL. The purpose of this alignment was to reduce the risk of vacuum leaks by making the synchrotron radiation (SR) irradiation point on the flange vertically symmetric, because the beam pipe temperature downstream of the wiggler section tended to increase asymmetrically. After the alignment work, the frequency of SBL events increased (see the area outlined in orange in Fig. 9), accompanied by pressure bursts in the aligned section. This temporal correlation raised the possibility that the alignment work contributed to the increase in SBL events.

It should be noted, however, that the beam current also increased slightly during this highlighted period. Consequently, it is difficult to unambiguously determine whether the increase in SBL frequency was primarily induced by the beam pipe realignment or by the elevated beam current. Nevertheless, this correlated trend served as a critical clue that prompted us to suspect a relationship between dust within the beam pipe and SBL events.

This observation motivated us to consider that interactions between dust particles and the beam might be responsible for SBL events. This hypothesis is supported by experience from Phase-1 operation, during which beam aborts were frequently triggered by phase oscillations caused by energy shifts following collisions between dust particles and the beam. Although such gradual, millisecond-scale beam losses were no longer observed after Phase-2, two key observations renewed interest in dust as a possible origin of SBL: (1) the pressure bursts

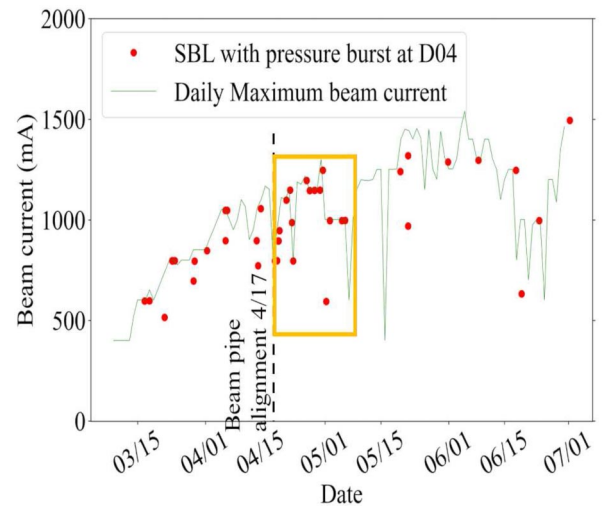


FIG. 9. Number of SBL events accompanied by the pressure bursts at the location within the D04 wiggler section where the beam pipe was realigned during the 2024ab run. The region enclosed by the orange rectangle indicates the period during which SBL events increased following the beam pipe realignment.

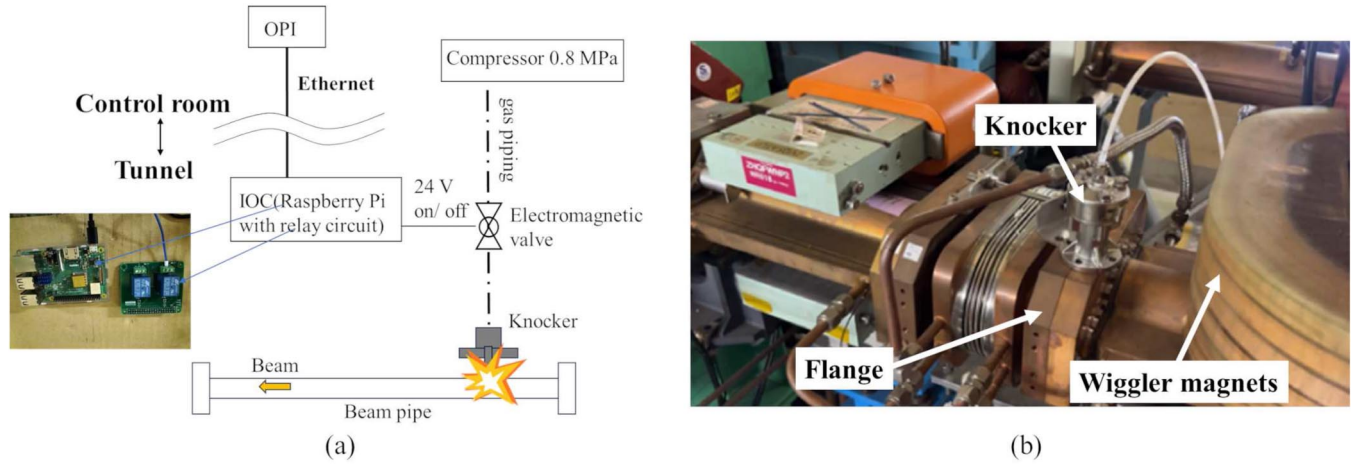


FIG. 10. (a) Schematic of the system. (b) Photograph showing the knocker attached to the flange of the beam pipe.

accompanying SBL events resemble those recorded during Phase-1 dust-related aborts and (2) the frequency of SBL events increased after the beam pipe realignment (or the associated slight increase in beam current).

During Phase-1 operation, a knocker study was performed. In this study, a mechanical knocker was used to strike the beam pipe to release dust trapped in surface grooves, thereby artificially reproducing gradual beam loss together with pressure bursts [20].

During the 2024ab run, a knocker study was performed under high-current beam operation to evaluate the hypothesis that dust particles contribute to SBL events. The wiggler sections (D04, D10, and D11) were selected as the installation location for the knocker because of the frequent occurrence of pressure bursts in this area during SBL events. Figure 10 shows a schematic of the knocker

system and a photograph of the knocker installed on a beam pipe flange. This figure (a) shows that the system operates using compressed air, with the knocker becoming functional upon the activation of a trigger signal sent to the 3-way valve. In this system, a Raspberry Pi was employed as the input output controller (IOC), with a relay circuit mounted on top of the Raspberry Pi. This configuration provides a cost-effective and highly portable solution, enabling knocker studies at various locations around the ring.

Figure 11 illustrates a representative result of the knocker study. The figure displays the pressure readings near the knocker installation site, the beam current, BG levels observed at the IP, and the knocker trigger signal. The knocker was configured to strike the beam pipe when the trigger signal changed from 1 to 0. Knocking produced

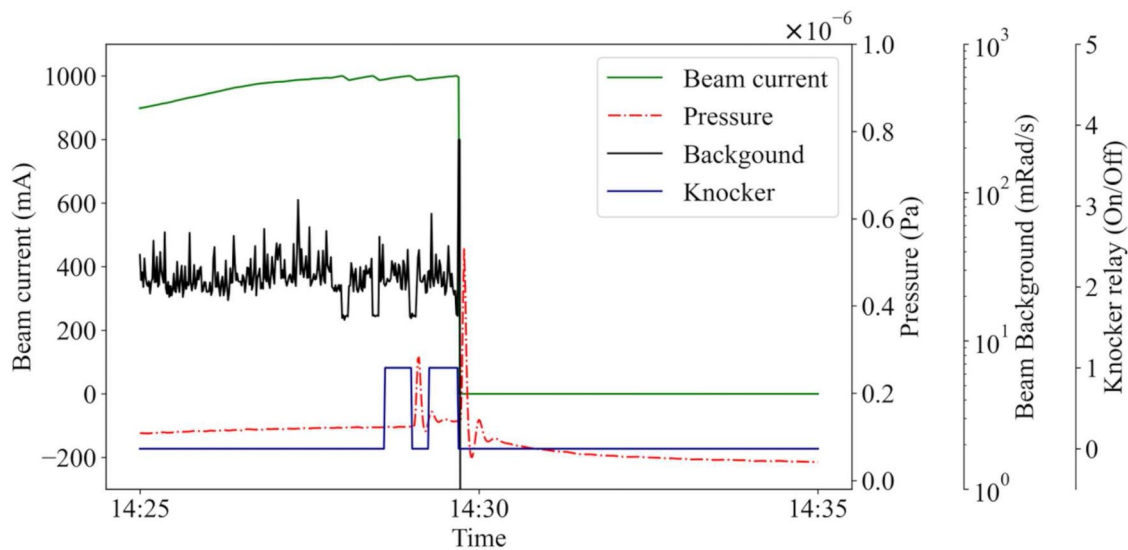


FIG. 11. Changes observed in beam current, pressure, and BG value during the knocker study. The second knocker activation resulted in a beam abort.

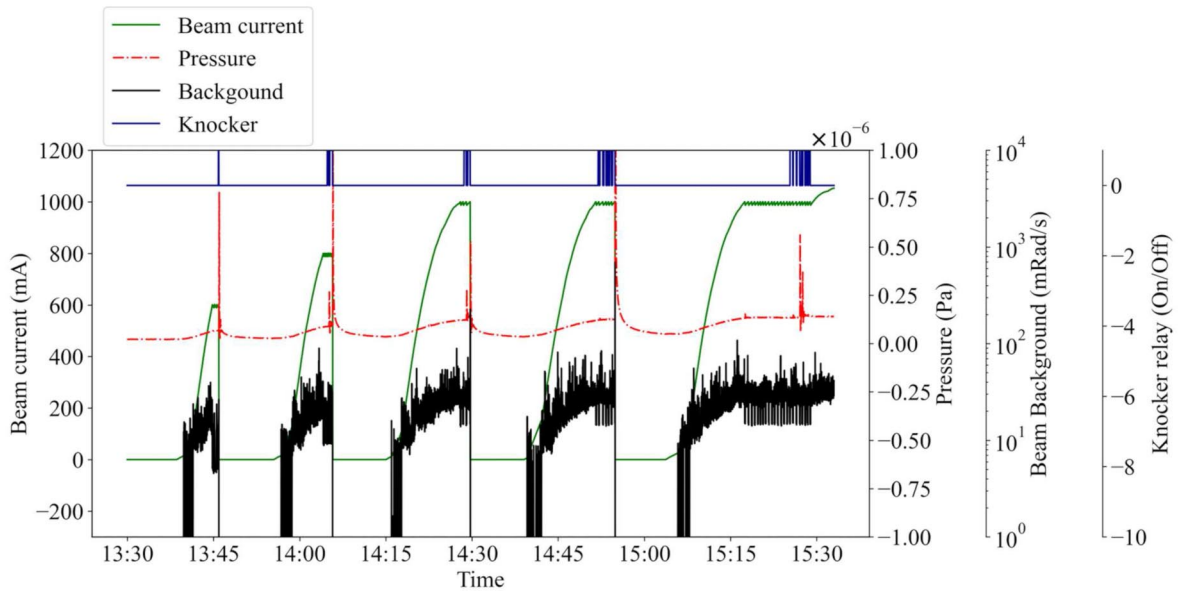


FIG. 12. Variation in beam current, pressure, and BG values over time during knocker study.

a pressure burst and a beam abort, accompanied by a noticeable increase in BG. An SBL event was also observed during this beam abort. This knocker study therefore enabled artificial reproduction of an SBL for the first time.

To evaluate the reproducibility quantitatively, the statistics were summarized based on the tested locations under high-beam-current conditions (exceeding 500 mA). Under the high-current condition, knocker studies were conducted at 12 distinct locations within the wiggler section. Beam aborts were successfully induced at 11 of these locations, among which 8 locations exhibited an SBL event with a beam loss of 5% or more, while the remaining 3 locations resulted in smaller losses below 5%. In contrast, when the knocker was applied to the normal drift chamber sections, pressure bursts were clearly observed, but no beam aborts were triggered.

Figure 12 demonstrates the effects of repeated knocking on the beam pipe during beam operation. Over time, the frequency of beam aborts decreased as knocking continued at the same location. Initially, beam aborts were observed during the first three knocker activations. However, following the fourth abort, subsequent activations did not induce any further beam aborts, suggesting an aging effect due to continuous knocking.

Based on the successful reproduction of SBL during the knocker study, we hypothesized that interactions between dust particles and the beam could be the main cause of SBL. To further test this hypothesis, we performed discharge experiments using clearing electrodes to verify whether dust generated during discharges could also induce SBL, motivated by Ref. [21]. In the SuperKEKB LER wiggler section, the beam pipe is equipped with clearing electrodes [22] to suppress the electron-cloud

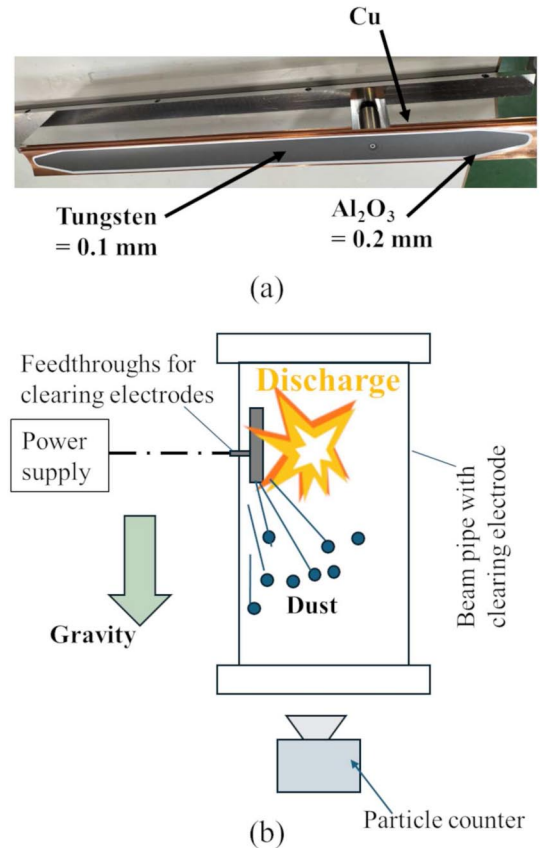


FIG. 13. (a) Clearing electrode before attachment to the beam pipe. (b) Experimental setup for measuring dust particles during discharge at the clearing electrode.

effect. During the 2024ab run, no electron cloud instability was observed; therefore, only a low voltage (approximately 10 V) was applied to the clearing electrodes.

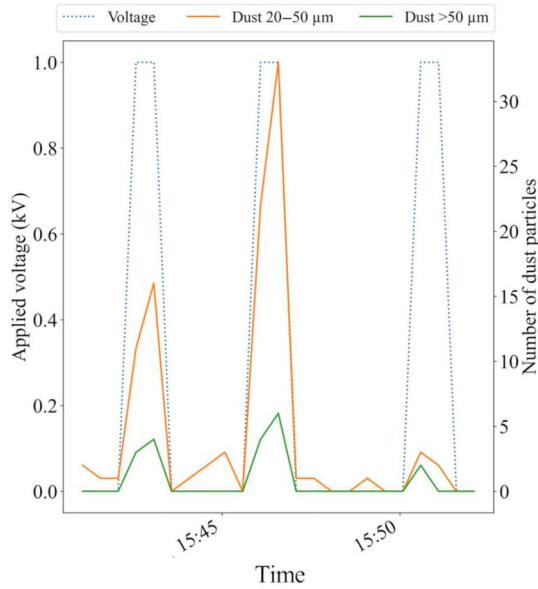


FIG. 14. Results of dust particle measurements during discharge at the clearing electrode.

Laboratory measurements were conducted to determine whether discharges at the clearing electrodes generate dust. Figure 13(a) shows the clearing electrode before assembly with the beam pipe. The clearing electrode consists of an alumina coating on a copper base covered by a tungsten layer and is installed on the upper inner surface of the wiggler-section beam pipe. Figures 13(b) and 14 illustrate the experimental setup and results, confirming that dust was generated during discharging. The collected dust particles had diameters ranging from less than $10\text{ }\mu\text{m}$ to greater than $100\text{ }\mu\text{m}$. Elemental analysis of the collected dust using a particle counter indicated that the dust consisted of copper and alumina,

which are materials commonly used in accelerator components.

Figure 15 shows results from the discharge study in the LER, in terms of beam current, pressure near the high-voltage clearing electrode, and the voltage applied to them. The data suggest that a pressure burst and a beam abort (corresponding to an SBL event) occurred almost simultaneously with the voltage trip associated with the discharge at the clearing electrode. This temporal coincidence suggests that dust generated during discharge may contribute to SBL events. In addition, as described earlier, the dust generated during discharge at the clearing electrode was composed of copper and alumina, indicating that dust composed of common accelerator materials can be associated with SBL events.

Based on the results of these two experiments during the 2024ab run, interactions between dust particles and the beam were considered the primary candidate cause of SBL. Visual inspection of the inner surface of the clearing electrode during atmospheric opening did not reveal any abnormalities. In addition, no unintended discharge of the clearing electrode was observed during the 2024ab run. Consequently, the location within the beam pipe at which the dust particles were generated could not be identified during the 2024ab run.

B. Effect of clearing the black stain

During the 2024 c run, spanning November 2 to 5, the QCS experienced three quenching events attributed to SBL. These SBL events were accompanied by pressure bursts detected by the second and third vacuum gauges in the D10 section, identified as D10L02 and D10L03. In response, the bellows beam pipe situated between these gauges was removed for internal inspection. The inspection confirmed that the clearing electrode remained intact,

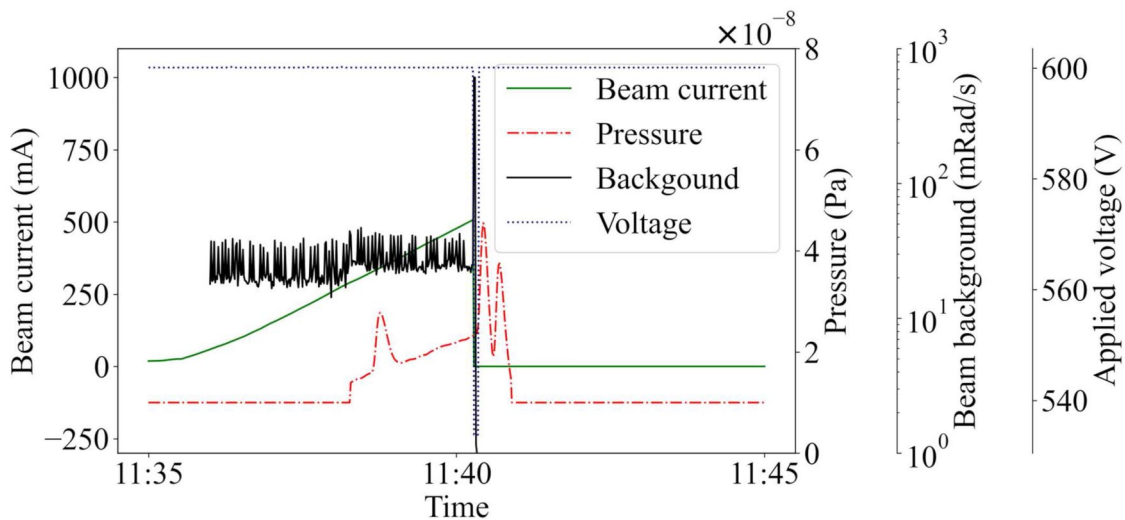


FIG. 15. Variation in beam current and pressure during discharge observation at the clearing electrode.

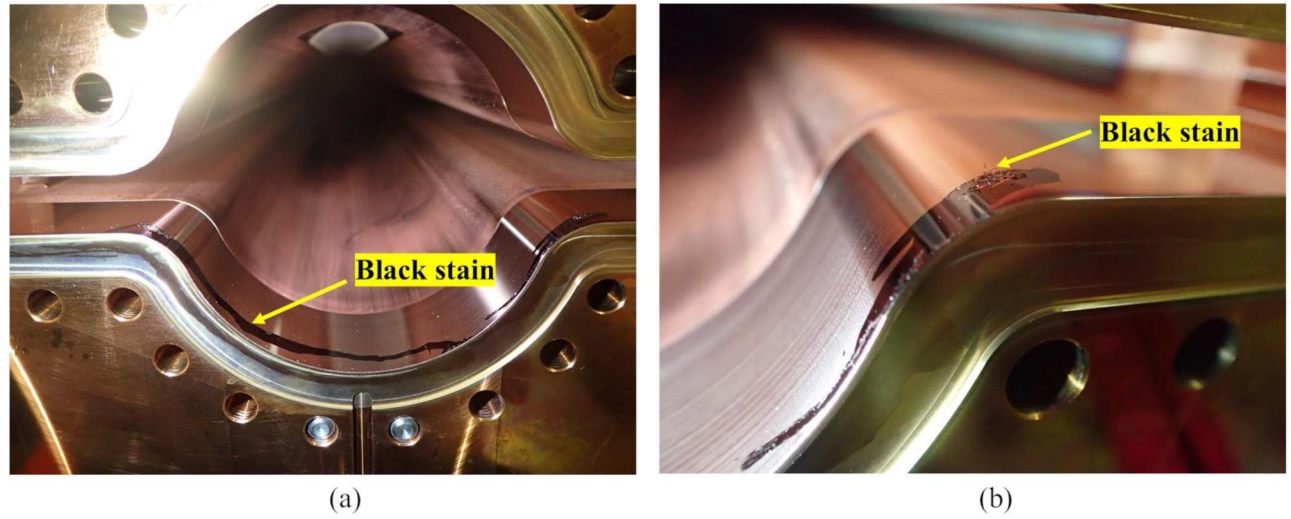


FIG. 16. Black stains observed on the inner surface of the beam pipe in the D10 wiggler section. (a) Entire inner surface of the beam pipe. (b) Close-up view of a black stain.

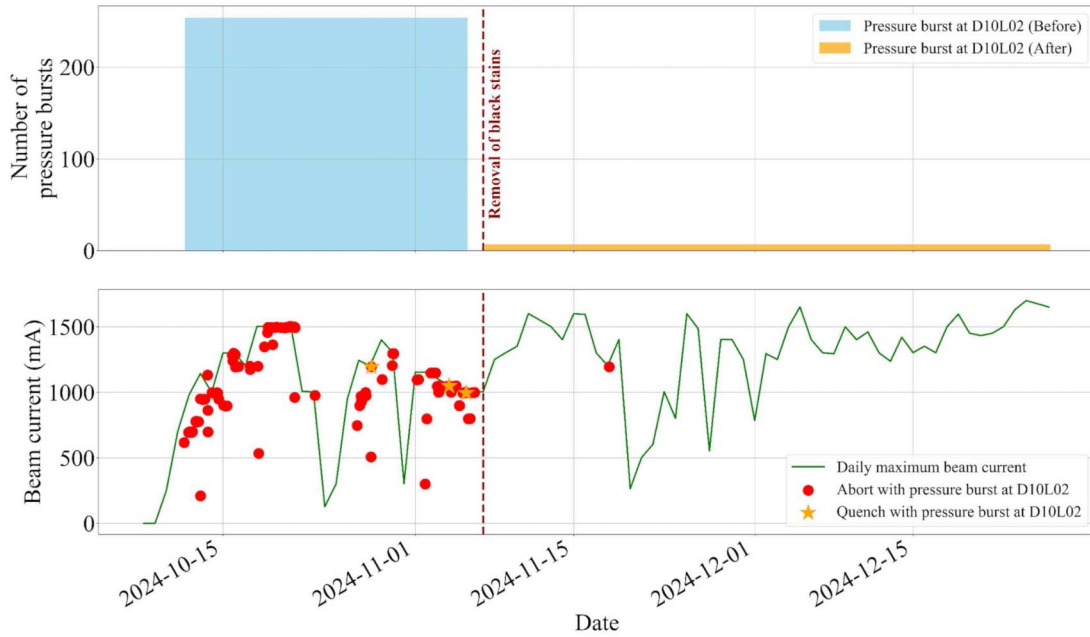


FIG. 17. Comparison of SBL events and pressure bursts before and after the removal of black stains. The vertical dashed line indicates the timing of the black stain removal, labeled "Removal of black stains." The green line represents the daily maximum beam current.

with no signs of delamination or coating damage. However, black stains were observed on the flanges of the bellows pipe, the beam pipe of the quadrupole magnet, and the beam pipe equipped with the clearing electrode. Figure 16 shows a photograph of black stains on the flange region inside the beam pipe. The black stains are visible around the entire circumference of the flange, as shown in Fig. 16.

After cleaning the black stains and reinstalling the bellows beam pipe, the rate of SBL went down. Figure 17

compares the occurrence of SBL events accompanied by pressure bursts at D10L02 before and after removal of the black stains. Before removal, SBL events occurred near the maximum beam current achieved on each day. After removal of the black stains, SBL events were rarely observed, even when the maximum beam current increased. This comparison indicates a clear change in SBL occurrence following removal of the black stains.

On November 6, 2024, black stains were removed from sections D10L02 and D10L03, after which a significant

reduction in SBL events was observed. Based on this outcome, black stains were also removed from other sections (D10L07 and D10L08). At these locations, seven beam abort events accompanied by pressure bursts were observed before removal, whereas no such events were observed after removal.

IV. LABORATORY INVESTIGATION OF BLACK STAINS

We conducted laboratory investigations into the black stains observed inside the beam pipe. The main points of investigation included its structure, component analysis, and origin (in Sec. IV A), as well as the mechanism by which such stains appear inside the beam pipe (in Sec. IV B).

This section describes the results of this investigation.

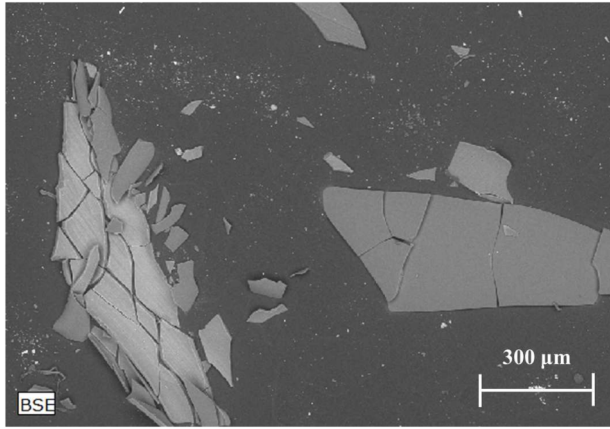


FIG. 18. SEM image of a piece of black stain collected from inside the beam pipe in the D10 wiggler section.

A. Analysis of black stains and artificial production of black stains

To investigate the details of the black stains, we performed microstructural analysis using scanning electron microscopy (SEM). We also analyzed the composition using Raman spectroscopy. Figure 18 shows an SEM image of the black stain, revealing a flake-like structure.

The black stain was found on a flange where vacuum sealant had been injected using a syringe, suggesting that the stain originated from the vacuum sealant.

To examine whether vacuum sealant forms black stains when irradiated with SR, irradiation tests were conducted at the Photon Factory Beamline 21 (PFBL21). SR was directed onto a copper plate sample coated with vacuum sealant. The vacuum sealant was applied on the copper substrate using a brush to a thickness of approximately 100 μm . The test system and the sample before irradiation

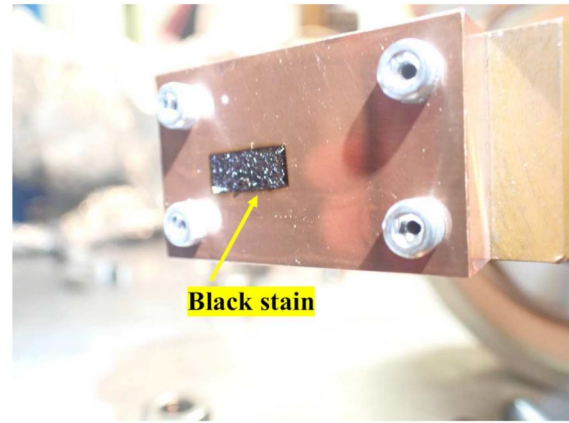
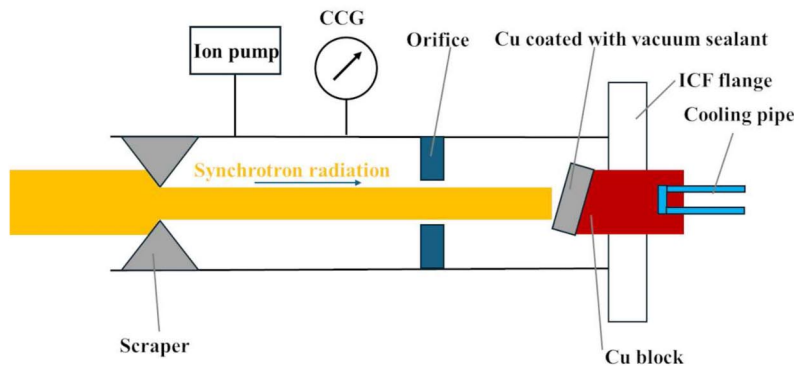
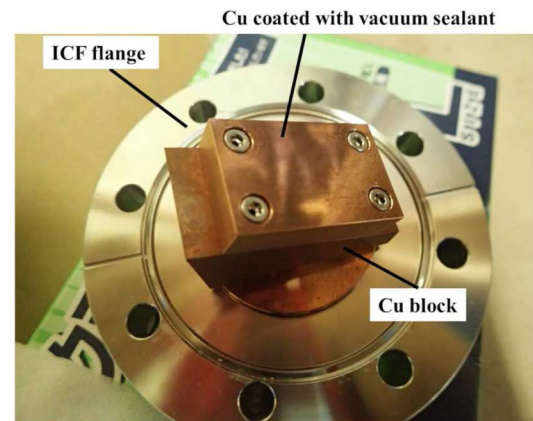


FIG. 20. Photograph of result of SR irradiation to vacuum sealant. Black stain was deposited.



(a)



(b)

FIG. 19. (a) Schematic diagram of the SR irradiation system used for the vacuum sealant test. (b) Photograph of the sample for SR irradiation and its mounting jig.

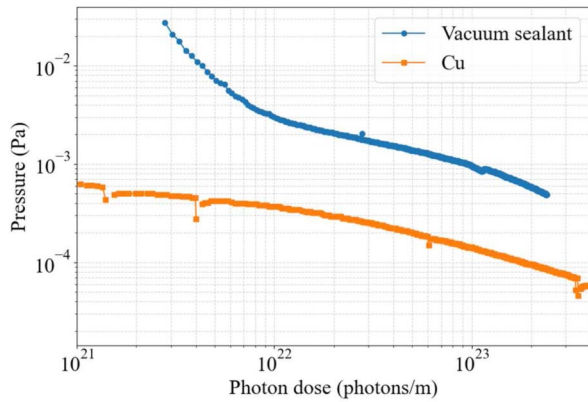


FIG. 21. Pressure value changes during SR irradiation of vacuum sealant and copper.

are shown in Fig. 19. The critical energy of the SR was 4 keV, and this beam was shaped using a scraper with a horizontal aperture of 10 mm and a vertical aperture of 5 mm. The sample was irradiated with SR in a beam spot of approximately 12×5 mm at a linear photon flux (dose rate) of 3.2×10^{18} photons/s/m. The irradiation was continued until the total integrated photon dose reached approximately 2.3×10^{23} photons/m for the vacuum sealant sample and 3.5×10^{23} photons/m for the copper reference sample. An orifice was installed upstream of the sample. Figure 20 shows a photograph demonstrating that black stains were artificially reproduced as a result of SR irradiation of the vacuum sealant. The experimental system was designed to measure photon-stimulated desorption by installing one Bayard-Alpert thermal ionization gauge and one residual gas analyzer upstream and downstream of the orifice, respectively. However, when SR was irradiated onto the vacuum sealant, the extremely high outgassing rate raised concerns regarding gauge degradation. Therefore, in this study, pressure measurements were performed using only the cold cathode gauge (CCG) installed upstream of the orifice.

Figure 21 shows the pressure values inside the chamber on the irradiated sample side plotted against the photon dose on the horizontal axis. The pressure values were calculated using the orifice conductance value and ion pump pumping speeds, assuming nitrogen gas. At the beginning of the irradiation (in the lower photon dose region), data points for the vacuum sealant are missing because the initial outgassing was so intense that the pressure exceeded the operational upper limit of the CCG, preventing the application of high voltage to the gauge. As the photon dose increased, the pressure gradually decreased. This behavior is attributed to both the typical beam conditioning effect and the chemical composition changes or depletion of volatile outgassing sources within the vacuum sealant under SR irradiation. To establish a baseline for comparison, a bare copper sample without the vacuum sealant was

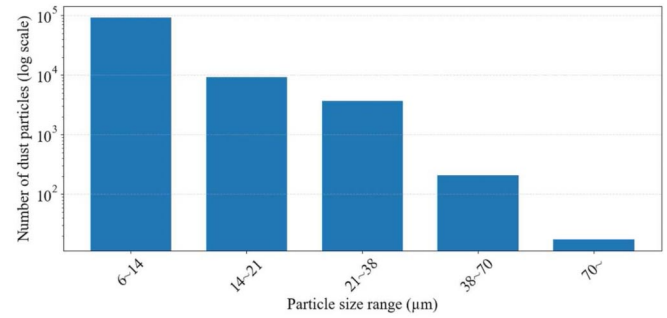


FIG. 22. Particle size distribution of dust extracted from artificially produced black stain (irradiated with SR at PFBL21). The horizontal axis represents particle size range, and the vertical axis shows the number of particles.

also irradiated under the same experimental conditions as a reference. The measured pressure value for the vacuum sealant sample was extremely high—approximately one order of magnitude higher than that observed for the bare copper reference sample, when the photon dose was below 1×10^{22} photons/m².

To further investigate the properties of the artificially produced black stains, the stains were subjected to ultrasonic cleaning in an organic solvent, and the extracted dust particles were analyzed for particle size distribution in accordance with ISO 4406 [23]. This standardized method enabled a quantitative assessment of the level and size distribution of solid particle contamination present in the black stains. Figure 22 presents a bar graph of the particle size distribution, with the particle size range on the horizontal axis and the number of dust particles on the vertical axis. The sample used for this measurement was an artificially produced black stain generated at PFBL21. To eliminate the influence of dust originating from regions not irradiated by SR, a control measurement was performed using a copper sample coated with vacuum sealant but not irradiated. The number of particles detected from the

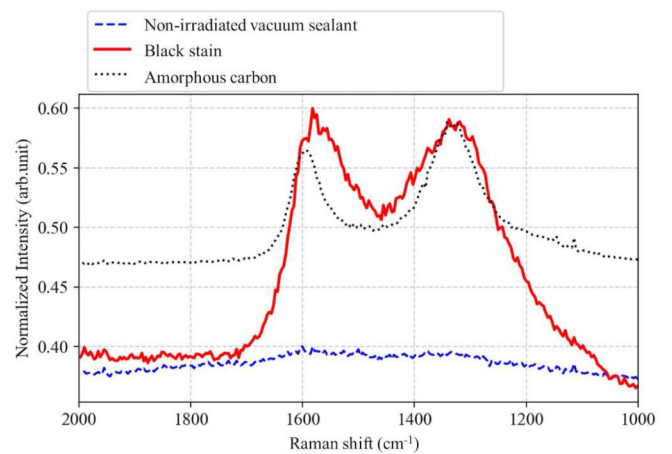


FIG. 23. Raman spectroscopy results for black stain, non-irradiated vacuum sealant, and amorphous carbon.

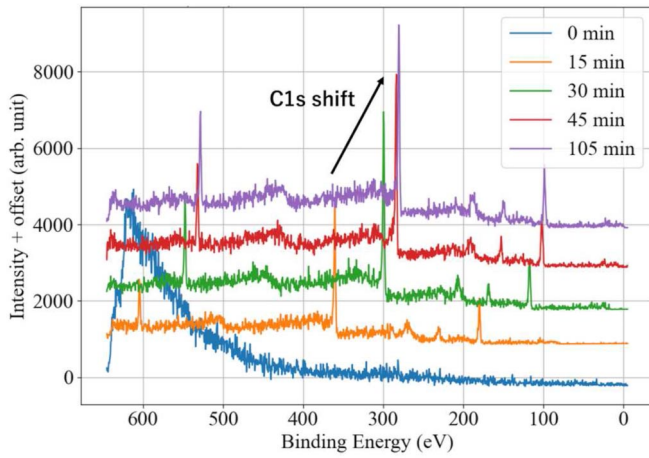


FIG. 24. The SR (white light) generated from the undulator was irradiated onto the vacuum sealant applied to a copper substrate, and the changes before and after irradiation were evaluated using x-ray photoelectron spectroscopy (XPS) measurements.

unirradiated sample was subtracted from that of the irradiated sample, and the resulting values were plotted. Furthermore, as suggested by the numerical calculations and laboratory experiments reported in [24,25], this dust generated by SR irradiation on the vacuum sealant may also be attracted toward the stored beam.

Initial component analysis of the black stain using energy-dispersive x-ray spectroscopy (EDS) detected silicon, oxygen, and carbon. As this stain was black in color, it was assumed to have a high carbon content. However, because EDS has low precision for carbon analysis, we decided to analyze the stain using Raman spectroscopy. The results of analyzing the black stain using Raman spectroscopy are shown in Fig. 23. For comparison, the analysis results for the vacuum sealant in its commercially available state and commercially available amorphous carbon are also plotted in this figure. This figure indicates that the black stain had a signal shape similar to that of amorphous carbon. This result also shows that the signal was completely different from that of the nonirradiated vacuum sealant. Therefore, even if the black stain originated from the vacuum sealant, its composition changed due to some influence.

Because Raman spectroscopy alone provided only limited evidence for the carbonization of the vacuum sealant, we also performed x-ray photoelectron spectroscopy (XPS) analysis of the vacuum sealant samples before and after SR exposure. Figure 24 presents the results of XPS measurements conducted at PFBL13B. In this experiment, samples were prepared by applying a vacuum sealant onto copper substrates and subsequently irradiated with undulator radiation (white synchrotron light) for varying durations. XPS spectra were collected as a function of irradiation time. For the sample with no irradiation

time, significant charging effects were observed, which resulted in the absence of prominent signals in the XPS spectrum. As the irradiation time increased, the C 1s binding energy shifted, and the intensity of the corresponding peak progressively increased. These results indicate that irradiation promotes the progressive carbonization of the vacuum sealant on the copper surface.

B. Investigation of vacuum sealant permeation into beam pipes

In high-current electron/positron storage-ring colliders such as the SuperKEKB MR, short bunch lengths and substantial synchrotron radiation power are characteristic features. To satisfy these operational requirements, the SuperKEKB LER employs the MO flange as the primary beam-pipe flange. The MO flange is a specialized vacuum flange developed to drastically reduce beam impedance by minimizing steps and gaps at the connections, thereby smoothly joining beam pipes with complex cross sections (such as antechambers) to suppress high-frequency electromagnetic disturbances and prevent beam instabilities [26]. This represents the first implementation of MO flanges in a storage-ring collider. The principal motivation for selecting the MO flange was the necessity of incorporating an antechamber structure as part of the electron-cloud mitigation strategy in the positron ring. Considering the combination of high beam currents and short bunch lengths at SuperKEKB, conventional rf-contact flanges equipped with rf fingers—commonly used in SR storage rings—were judged insufficiently robust under such extreme conditions. Although alternative flange types could be adopted by locally modifying the beam-pipe cross section to a circular geometry, such modifications increase the risk of trapping higher-order modes. For these reasons, MO flanges were used throughout the LER.

In the SuperKEKB HER, both Helicoflex and MO gaskets are employed for beam-pipe flange connections. Regardless of whether a Helicoflex or MO gasket is used, the high SR power in the SuperKEKB MR and the accompanying thermal cycling frequently lead to vacuum leaks.

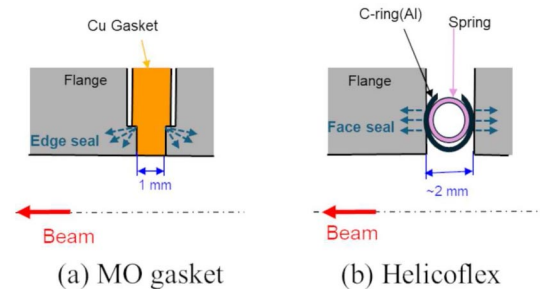


FIG. 25. (a) Schematic illustration of the MO gasket and (b) schematic illustration of the Helicoflex gasket.

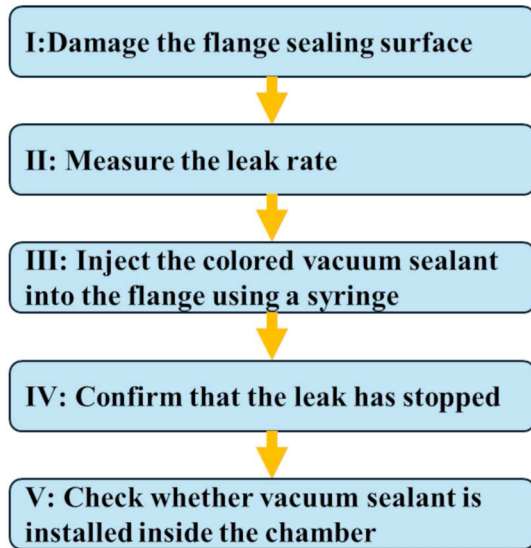


FIG. 26. Experimental procedure for evaluating vacuum sealant penetration through an MO flange. Steps include: (I) introduction of a scratch on the flange surface, (II) leak rate measurement, (III) injection of colored vacuum sealant, (IV) confirmation of leak sealing, and (V) inspection of sealant intrusion into the beam channel.

A schematic illustration of the MO and Helicoflex gaskets used in SuperKEKB is shown in Fig. 25. The MO gasket was sealed by compressing an annealed, softened metal gasket against a flange with a sharp sealing edge. In contrast, the Helicoflex gasket consists of an aluminum C-ring containing an internal helical spring. As shown in the figure, the MO gasket provides an edge-type seal, whereas the Helicoflex gasket forms a face-type seal. From the perspective of the beam, the MO gasket structure results in a smaller geometric discontinuity (step) at the flange joint compared with Helicoflex, leading to a more continuous inner surface for the beam pipe. Notably, black stains were frequently observed at the locations where the MO gaskets were used. In contrast, although a vacuum sealant was applied to address leaks in the arc sections of the HER using Helicoflex gaskets, the occurrence of black stains was rare in these regions.

We conducted a series of laboratory investigations to elucidate the mechanism by which the vacuum sealant penetrates the interior of the beam pipe—particularly in the case of MO gaskets. The procedure for evaluating the ingress of vacuum sealant is depicted in Fig. 26. First, an artificial scratch was introduced onto the sealing surface of the flange using a force gauge (Step I), followed by a leak test on the assembled flange. The experiment confirmed the presence of a measurable leak rate in the 1×10^{-10} Pa m³/s range (Step II). After determining the leak rate, a colored vacuum sealant was injected through the leak groove of the flange for leak testing using a syringe that effectively stopped the leak. The vacuum sealant was colored using a dye penetrant typically

employed for weld inspections. To ensure that the sealant reached the leakage point more easily, the vacuum sealant loaded into the syringe was diluted threefold with acetone before injection (Step III). The total volume of the vacuum sealant injected into the syringe was 3 mL. Both the dilution method and the injection volume were based on the standard procedures used during actual accelerator maintenance. Following Step III, a leak check was performed to confirm that the leak had been successfully sealed (Step IV). Subsequently, the flange connection was disassembled, and the interior of the beam channel was inspected to verify whether the colored vacuum sealant had penetrated into the beam pipe (Step V).

Figure 27 presents the photographs captured during the experiment and the leak rate measured during the leak check. The photograph corresponding to Step I shows the process of scratching the flange surface using a force gauge. The photograph of Step IV depicts the injection of the colored vacuum sealant into the flange using a syringe. The leak rate plot demonstrates that the leakage was successfully stopped after the sealant was injected. The photograph of Step V reveals that the colored vacuum sealant has penetrated the beam channel.

This experiment was performed five times using both the MO and Helicoflex gaskets. In the case of the MO gasket, penetration of the vacuum sealant into the beam channel was observed in four out of five trials. In contrast, for the Helicoflex gasket, no sealant penetration was observed in any of the five trials. These results indicate that the vacuum sealant is more likely to intrude into the beam channel when MO gaskets are used. We speculate that this is because the MO gasket employs an edge-type seal, resulting in a shorter path for the sealant to reach the beam channel compared with the face-type sealing mechanism of the Helicoflex gasket.

These tests were conducted at a leak rate of 1×10^{-9} Pa m³/s, because this level provided high reproducibility for the experimental procedure. In actual accelerator operation, the typical leak rates observed in the ring are in the 1×10^{-11} to 1×10^{-10} Pa m³/s range; however, artificially reproducing such low leak rates in the laboratory is technically challenging. Therefore, the present experiment was performed under conditions that were more susceptible to vacuum-sealant penetration than those encountered in the SuperKEKB.

V. DISCUSSION OF THE RESEARCH FINDINGS AND SUMMARY

Two studies using the LER beam indicate that SBL is most likely associated with beam-dust interactions. The investigations described in the previous sections clarified the process by which vacuum sealant penetrates the beam pipe, demonstrated that vacuum sealant develops into black stains under SR irradiation, and identified the formation mechanism of these black stains. Experimental results

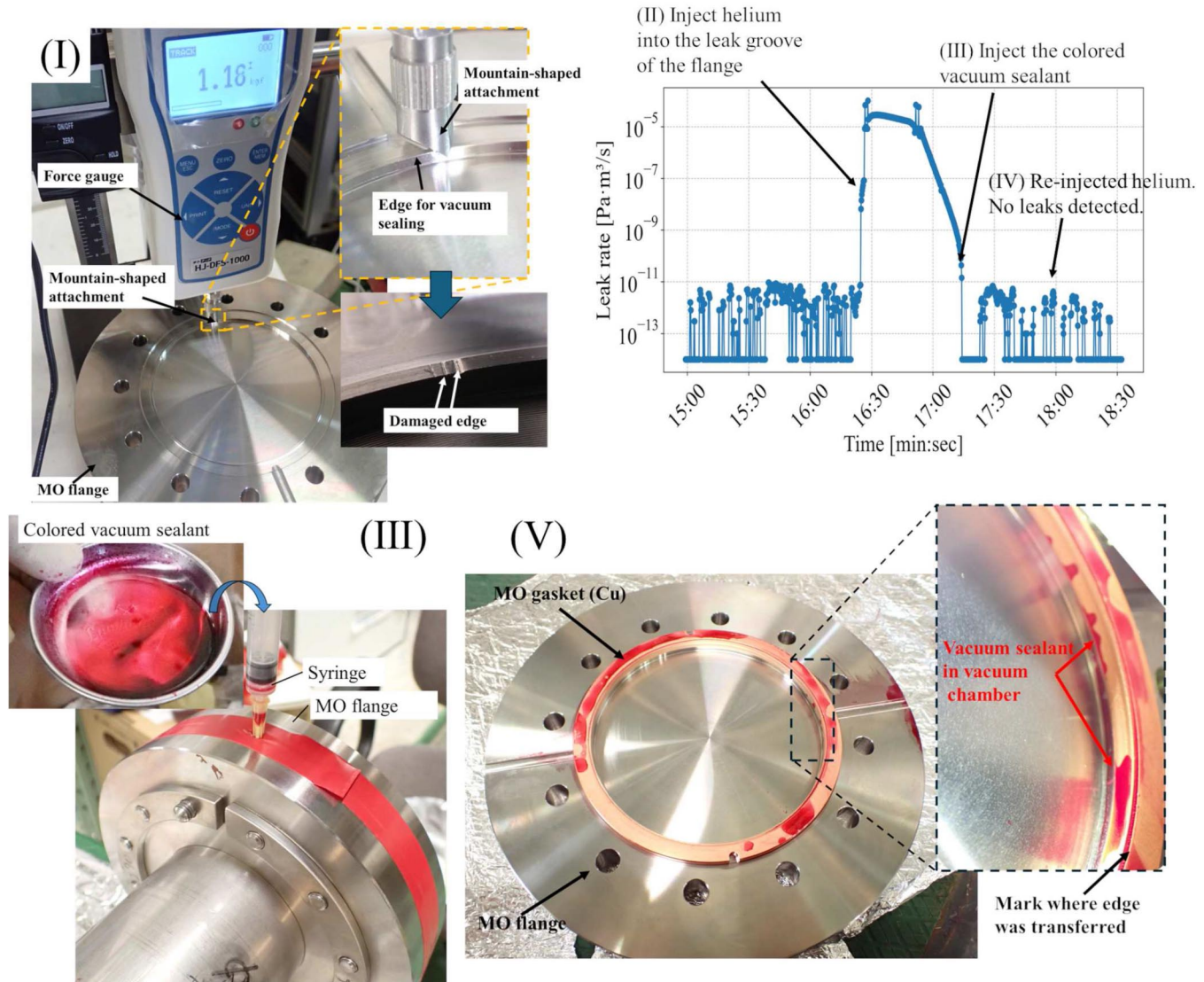


FIG. 27. Photographs and leak rate measurements during the vacuum sealant penetration test for an MO flange. Step I: Scratching the flange surface with a force gauge. Step III: Injection of colored vacuum sealant. The leak rate plot confirms successful sealing by vacuum sealant (Step II–IV). Step V: Colored sealant observed penetrating into the beam channel.

further showed that the black stains are more prone to fragmentation into dust than nonirradiated vacuum sealant. As reported in the literature [27], numerical simulations also reproduced beam behavior consistent with SBL events, demonstrating that the interaction with dust particles induces rapid beam size growth, which subsequently triggers beam loss. However, these simulation models do not yet fully explain the entire loss dynamics and the exact scale of the beam loss. To achieve a more comprehensive understanding, further refinements to the simulation codes are currently underway.

Extensive experimental studies conducted both with and without beam operation have substantially advanced understanding of SBL, which had previously remained largely unexplained. However, a complete understanding of SBL has not yet been achieved. Experiments that

could directly test the phenomenon, such as intentionally introducing dust particles of known size and mass into the beam to induce SBL, are prohibited at SuperKEKB for safety reasons.

Although vacuum sealants have been identified as a significant source of dust contributing to SBL, complete elimination of SBL events is presumed to be unfeasible because such events can also be triggered by dust generated through electrical discharges. Similar dust-beam interactions have been reported at other accelerator facilities; however, the severity of the associated effects is considerably lower than that observed at SuperKEKB. Based on the results of this study, SBL is most likely to occur in storage-ring accelerators that operate with high beam currents—sufficient to attract and potentially heat dust particles—and that have very small vertical physical

apertures. SBL may therefore also occur in future facilities such as FCC-ee and CEPC, which plan to employ the nano-beam scheme.

Despite the progress achieved in understanding SBL through these studies, mitigation of damage to particle detector sensors, particularly those of Belle II, remains a significant challenge. Ideally, interactions between the beam and dust particles inside the accelerator should be completely avoided. In fact, practical steps have already yielded promising results: following a large-scale removal of vacuum sealants in 2025, the SBL rate per integrated dose in the LER has successfully decreased to approximately one-half of the 2024 level as of June 10, 2026. This halving was achieved despite the fact that the operation time at high beam currents above 1500 mA in 2026 was significantly longer than that in 2024 (approximately 1400 h in 2026 versus only about 12 h in 2024). However, mitigating SBL in the HER remains highly challenging with no significant progress yet, and a definitive solution for the remaining SBL events in the LER has not yet been established. This might be related to the fact that, in high-current accelerators such as SuperKEKB, electrical discharges cannot be entirely eliminated, and the probability of dust-beam interactions cannot be reduced to zero through local component modifications alone. In future work, to prevent dust from being introduced into the accelerator vacuum components, meticulous fabrication, cleaning, and installation of these components under a clean environment will also become crucial. At present, several countermeasures are under consideration at SuperKEKB, including the development of more robust collimator systems capable of selectively intercepting abnormal beams while maintaining low impedance and minimizing the risk of discharge during normal operation. For future accelerator facilities, further improvements in the robustness of particle detectors will be essential.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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