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REPORT ON COLLIMATOR DAMAGED EVENT IN SuperKEKB

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Abstract

Collimator jaws for SuperKEKB were installed to suppress the background noise (BG) in a particle detector complex named Belle II. The collimators could reduce the BG when the collimator was closed [1]. However, in high-current (>500 mA) operations, the jaws become occasionally damaged by hitting abnormal beams. This problem occurs with a low frequency of once in a commissioning period (2–6 months), but has significant consequences, because high voltage cannot be applied on to the detectors in Belle II sometimes due to high BG. The cause of, which occurred this event, has not been clearly identified yet.

INTRODUCTION

SuperKEKB, which is an upgrade of the KEKB, is a high-luminosity electron-positron collider with asymmetric energies of 7 GeV (electron, high energy ring: HER) and 4 GeV (positron, low energy ring: LER). The design luminosity was 8×10^{35} cm^{-2} s^{-1} [2]. The beam commissioning of SuperKEKB proceeded in three steps. Phase-1 was completed in 2016. In Phase-1, the QCS and Belle II were not installed and no beam collision was performed. In Phase-2, the final focusing (quadrupole at collision section) superconducting (QCS) magnets and the main part of the Belle II detector were installed. However, a vertex detector (VXD) was not installed in Phase-2. The Phase-3 began in 2018. Prior to this phase, a VXD was installed. In this phase, we continue beam tuning aiming at the design luminosity in parallel with the physics experiment [3].

The event of the damage jaw triggered by an abnormal beam hitting occurred nine times (LER: 8, HER: 1) to date (5/9/2021). All the damaged jaws were in vertical collimators. We believe that, owing to the beam with an abnormal orbit and/or its oscillation in the ring for unknown reasons, the beam hit the jaw in the vertical collimator.

EVENT OF DAMAGED JAW

Overview

We installed two types of collimator as SuperKEKB-type, 10 horizontal and 5 vertical ones. The SuperKEKB-type collimator chamber is equipped with a pair of movable jaws. The vertical collimators are the point of the smallest aperture in the ring to prevent QCS quenching and depress BG. The jaw is 360 mm in length and 12 mm in width. We can replace the jaw with a new one if the jaw in use becomes defective. The jaw has a tungsten (or tantalum) block as the tip. Tungsten has a high melting point and a short radiation length (3.5 mm). The longitudinal length of the tip of the tungsten is 10 mm [1].

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The jaws damaged by the abnormal beam hitting are shown in Fig. 1. A scar-mark can be observed (Fig. 1 (a)) on the tip of the top jaw. When a beam passed through tungsten, it caused pair creation. Owing to its energy deposit, tungsten was sublimated as the temperature rose sharply. Then, a protrusion was formed by the vapor deposition of tungsten on the jaw on the opposite side (Fig. 1 (b)).

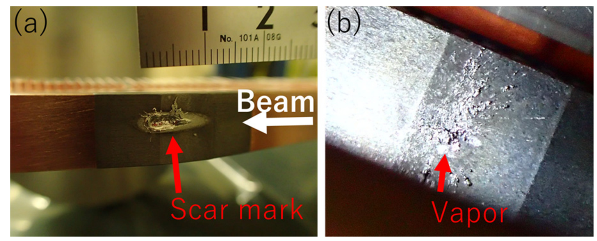

Figure 1: (a) Damaged jaw, (b) protrusion by vapor deposition on the opposite side of the damaged jaw.

Effect of the Event of Damaged Jaw

Figure 2 shows the LER beam current and the value of the BG observed using the VXD in Belle II before and after the jaw damage event. The peak value of the BG after this event was approximately 200 times higher than that before it. As the accelerator operation was difficult after this event due to the high BG, we replaced the damaged jaw with a new one during the 2020c run (from 10/14/2020 to 12/18/2020).

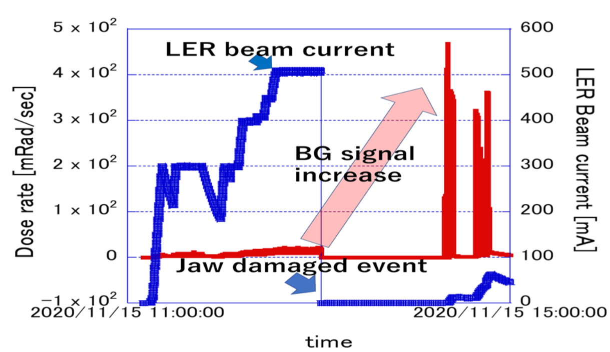

Figure 2: BG signal before and after the event of the damaged jaw.

When a jaw damage event occurred, a large beam loss was observed in Belle II. The soundness of the DEPFET pixel detector (PXD) in Belle II before and after the jaw was damaged during the 2019b run (from 4/1/2019 to 7/1/2019) is shown in Fig. 3. The white part in Fig. 3 (b) indicates that the modules in the PXD are no longer functioning [4]. It was revealed that an event during which the current collimator could not protect Belle II occurred.

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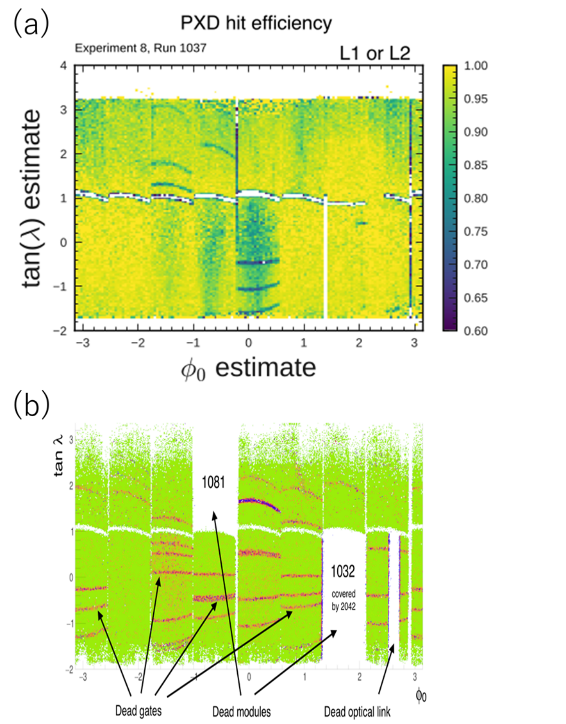

Figure 3: Soundness of the PXD (a) before and (b) after the jaw damage event that occurred during the 2019b run.

Cause of the Jaw Damage Event

In this event, the pressure burst near the collimator (blue line) with the beam abort is shown in Fig. 4. In addition, a smaller pressure burst (green line in Fig. 4) was observed at a location different from the location at which the collimator was installed. The beam abort during this event was mainly triggered by the beam loss monitor. It is believed that the pressure burst at the green line was caused by the beam interacting with the dust. We consider that these events were triggered by a sudden change in the beam energy because the beam collided with the dust. We consider dust to be the cause of these events because of two reasons.

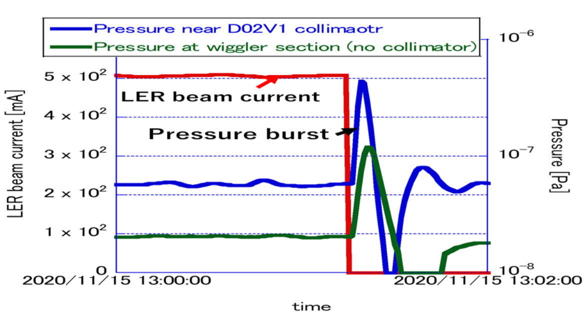

Figure 4: Pressure burst when a jaw damaged.

The first reason is that the beam operation was hindered owing to the influence of dust in the LER during Phase-1. This phenomenon caused by dust during Phase-1 was observed as the local pressure bursts accompanying beam losses [5, 6]. The pressure bursts mainly occurred near or inside the aluminum alloy beam pipes in dipole magnets. The longitudinal grooves in the beam pipes for the dipole magnets [7], which counteract the electron cloud effect, are likely to trap the dust particles during the manufacturing and installation processes.

We believe that the pressure bursts in Phase-1 were due to the interaction between the circulating beam and the falling dust particles, which were captured in the groove on the upper surface. It is believed that dust falls during the beam operation because the capture power of the groove is weakened as the beam pipe is warmed by synchrotron radiation. To demonstrate the cause of the dust particles, the pressure bursts and simultaneous beam loss were reproduced using the knocker, which vibrates the beam pipe in pulses and is attached to the aluminum alloy beam pipes in the dipole magnets. The probability of reproduction of the pressure bursts accompanying beam losses in this test was 100%.

During downtime after Phase-1, we attempted to collect the dust particles inside the beam pipe where pressure bursts were frequently observed. Several dust particles were collected inside the beam pipe. The main element constituting the collected dust particles was aluminum.

The frequency of pressure bursts increased when the beam current exceeded the recorded value, whereas it tended to decrease when the beam current remained almost constant. Thus, we decided to perform a normal physical run just below the maximum beam current.

Next, we describe the second reason. We illustrate the data obtained using the bunch oscillation recorder (BOR) (Fig. 5), where the horizontal axis represents the bucket number, and the vertical axis represents the product of the beam intensity and vertical beam position.

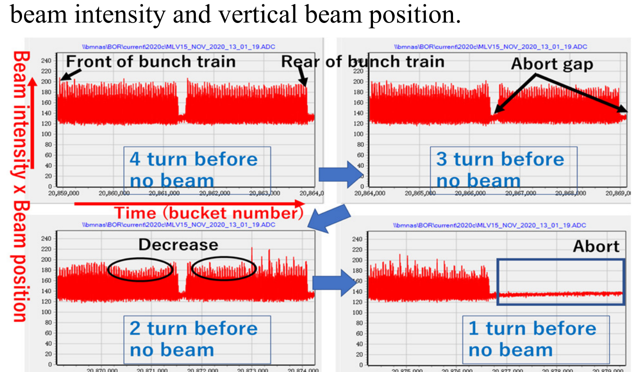

Figure 5: Plot observed using BOR when a jaw was damaged.

In conclusion, when this event occurred, there was no sign of oscillation indicating beam instability, and the data indicated that the intensity of the part of the bunch train suddenly decreased a few turns before the abort. We consider that part of the bunch train was abnormal upon interacting with the dust particles.

SIMULATION RESULTS

Fall Trajectory of the Charged-Up Dust

Assuming that the dust causes this event, a question arises as to why the phenomenon of the interaction between the beam and the dust occurs several times even

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though the beam size in SuperKEKB is very small. When the dust falls out of the groove, it almost does not interact with the beam if it is not attracted to the beam. Assuming that the beam has a circular transverse cross-section with a diameter of 2 mm and the material of the dust particles is aluminum, the probability of interaction between the dust falling from the groove and the beam is very low (see the black line in Fig. 6 (a)). We believe that the electron cloud may cause an increase in the probability of interaction between the dust and the beam. The mechanism is believed to be the charging of the free-falling dust when it passes through the electron cloud. Thereafter, the charged dust is drawn to the positron beam. Figure 6 (b) shows the orbit of the dust with the drawing force caused by the electron cloud, assuming that the energy of the charged-up dust is 50 eV [8] and the dust radius is 10 µm. If the above process occurs, the probability of interaction between the dust and the beam increases dramatically (see the red line in Fig. 6 (a)).

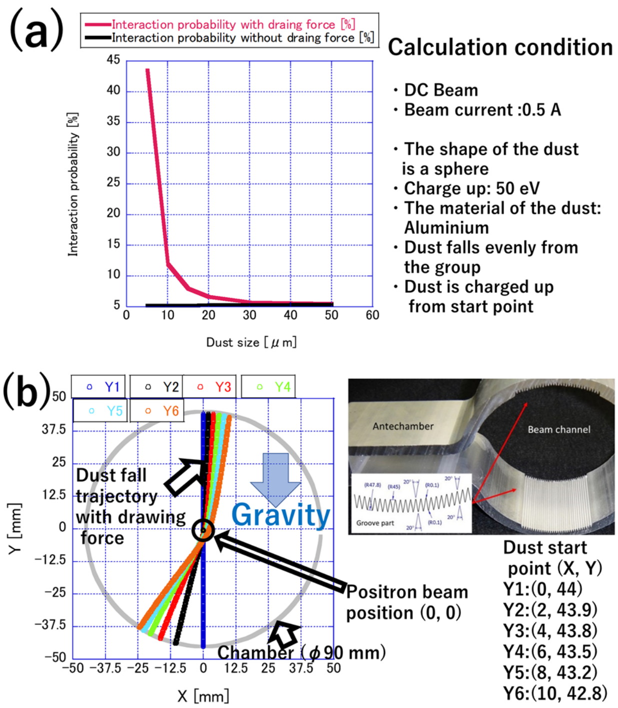

Figure 6: (a) Probability of interaction with/without the drawing force, (b) orbit of the dust (radius = 10 µm) with the drawing force caused by the electron cloud.

Tracking of Beam Interaction With Dust

We performed a beam tracking simulation to check whether the beam that interacted with the dust collided with the collimator. We assumed that the material of the dust particles was aluminum, the dust radius was 500 µm, and the interaction between the beam and the dust occurred at the location at which the pressure burst was observed. As it takes a considerable amount of time to investigate the interaction between a small dust particle and a beam, the calculation was performed with this size (500 µm). We tracked the scattered beam that interacted with the dust using PHITS [9] and Strategic Accelerator Design (SAD) [10]. Figure 7 shows the results of beam tracking when the D06V2 collimator jaw was damaged. See reference [1] for the collimator location. Figure 8 shows a comparison of the scatter plots of particles that collided with D06H1 and D06V2. We observed that the particles were concentrated within a narrow range in D06V2. If high-density particles hit the jaw, the jaw may be damaged.

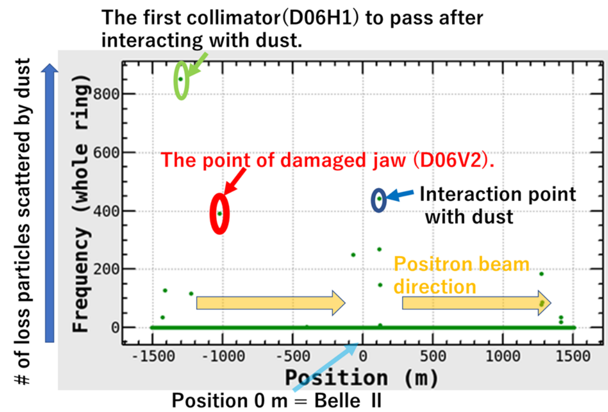

Figure 7: Result of tracking the scattered beam that interacted with dust using PHITS and SAD.

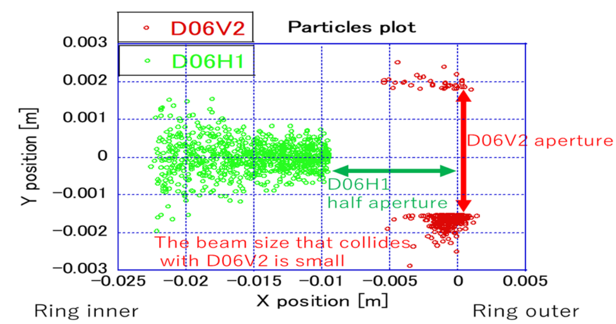

Figure 8: Comparison between the sizes of beams that collided with D06H1 and D06V2.

CONCLUSION

We conclude as follows:

- We believe that dust caused damage to the jaw, and accordingly, we described the reasons for this phenomenon. This is because this event is similar to the phenomenon triggered by the dust observed during Phase-1, and there is no sign of beam instability during sudden beam loss.
- We simulated the interaction between the beam and the dust. We showed that, if the dust becomes charged, its probability of interacting with the beam may increase. The simulation result of tracking the interaction of the scattered beam with the dust showed that there are a considerable number of particles hitting the damaged collimator.

Thus, we developed a low-Z collimator as a countermeasure for these events. This development has been reported in other studies [11].

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