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OBSERVATION OF SUDDEN BEAM LOSS IN SuperKEKB

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Abstract

SuperKEKB suffers sudden beam loss (SBL) during operation. It causes collimator damage, QCS quench and large beam background to the Belle-II detector. The beam aborts due to SBL is a major obstacle to store large beam/bunch current. Since cause of SLB is unclear, we launched an effort to investigate it and consider measures to be taken. In this paper, we discuss phenomena of SBL and various hypotheses to explain SBL.

INTRODUCTION

SuperKEKB is a collider handling 7 GeV electrons (HER) and 4 GeV positrons (LER), with a ring circumference of 3 km. Aiming for the world's highest luminosity, the nanobeam method was adopted. To achieve design luminosity, the βy* will be narrowed down by a factor of 20 and the beam current will be doubled with respect that of KEKB collider. Up to 2022b runs, we have achieved 4.7×10^{34} cm^{-2}s^{-1} with lower beam current than KEKB, with βy* =1mm which is much shorter than the natural bunch length of ～6mm [1][2]. The beam currents that recorded peak luminosity were 1.321 A for LER and 1.099 A for HER. The number of bunches used in FY2022 ranged from 783 to 2249, depending on the operating conditions. The primary goal of SuperKEKB is to increase luminosity more than 10^{35} cm^{-2}s^{-1}. An obstacle to this goal is sudden beam loss. The cause of sudden large beam loss is unknown, but it can cause damage to collimators (and other accelerator components), final focusing super conducting magnets (QCS) quenches, and large backgrounds to Belle-II detector. Also, it is not possible to store large currents because of beam abort. Therefore, a task force was set up to investigate and resolve the causes of the sudden beam loss.

OBSERVATION

It is necessary to protect the detectors and accelerator hardware from damage caused by high current beams. SuperKEKB has a fast beam abort system to abort the beam as soon as possible in the event of an abnormal situation [3,4,5]. The beam loss monitor system is used to trigger the abort of the beam [6]. Ion chamber (IC), PIN photodiode, and optical fiber are available as beam loss monitoring sensors; most of the PIN photodiodes are placed to the collimator of each ring to identify the ring where beam loss has occurred. ICs, on the other hand, are installed throughout the tunnel and cover a large space. Collimator locations in the ring are shown in Figure 1. The Belle-II detector installed in the interaction region (IR) is also equipped with a diamond sensor and scintillator-based detector as its own abort trigger.

Looking at the loss monitor at the time of abort occurrence, which was probably due to beam loss, we began to observe many instances of sudden beam loss occurring simultaneously in the entire ring collimator section and in the Belle-II detector. Figure 2 shows an example of the PIN and diamond signals at LER abort. The PIN signal appears to have a slow rise time due to the monitor circuit, but the start timing is within one turn (10μs) on all collimators, and the IR diamond signal is seen at the same time.

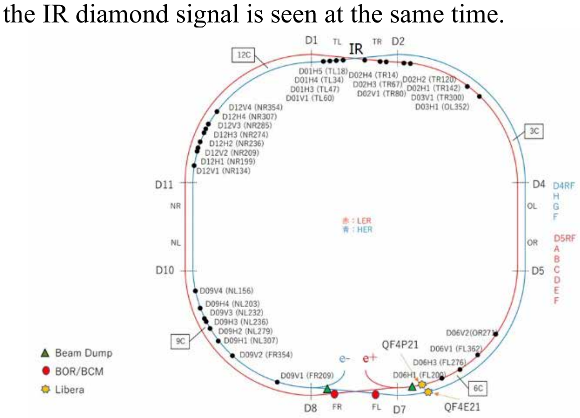

Figure 1: Overview of the collimator locations at SuperKEKB.

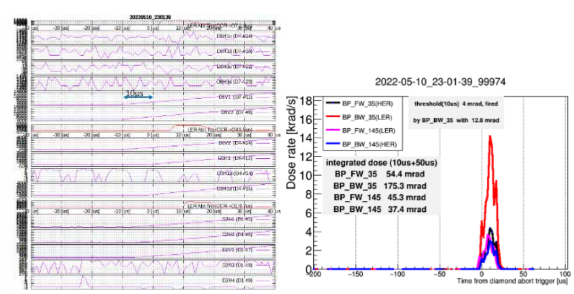

Figure 2: An example of (left)PIN and (right)diamond signals when an LER abort occurs.

In order to monitor the beam loss behaviour just before the beam abort, bunch current monitors with 4k turns of memory before the beam loss are used [7]. Figure 3 shows an example of the current change per bunch for HER and LER, where the first row shows the bunch current and the second row shows the difference in current from the previous turn; this corresponds to the lost beam current from the previous turn. The plot shows 6-7 turns before the abort,

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and it can be seen that the beam suddenly disappears just before the abort. Beam loss can occur in both HER or LER, but when loss occurs in LER, it is especially damaging to the collimator and Belle-II detector. We do not know if it happens in single beam operation or low current beam because we have not operated for a long time with those condition.

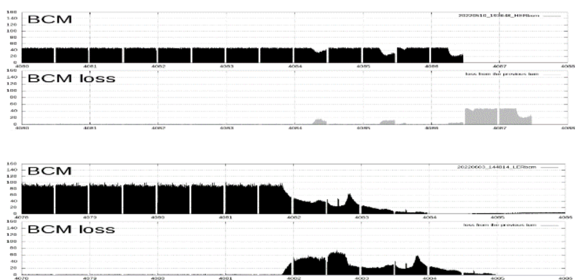

Figure 3: An example of the current change at feedback monitor position for each bunch of (top) HER and (bottom) LER.

Bunch oscillation can be measured simultaneously with bunch current, and the orbit can be calculated from the data, an example of which is shown in Figure 4. Just before the beam loss begins, the orbit appears to move, but the value is small, on the order of 0.1 mm. Even after the beam loss occurs, the orbit is changing by less than 1mm order at the FB monitor position. And no oscillations were observed that would be precursors to beam loss.

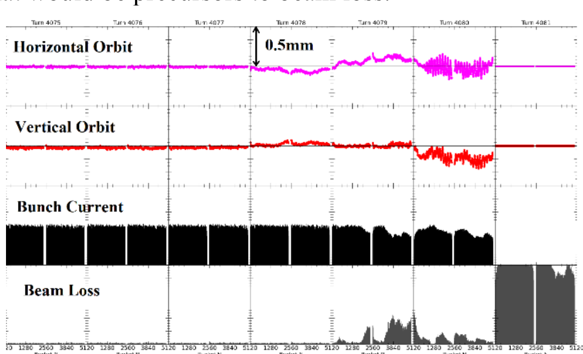

Figure 4: An example of bunch-by-bunch beam orbit variation and beam loss.

This sudden beam loss is most likely to occur when the beam current exceeds a certain bunch current. The first four of the 2022 LER sudden beam losses occurred within a day of increasing the beam current by a different number of bunches each, at above 0.7 mA/bunch; after the collimator (D6V1) damage on May 17, the threshold became somehow lower. This could be due to damage to the collimator, a change in the collimator configuration to reduce beam background, or other causes.

In the "sudden beam loss (SBL)" event, it appeared that the loss started at each collimator and IR within the same turn. To identify where the loss started first in the ring, a loss monitor specialized for timing measurements was placed in the ring [8]. Those loss monitors were attached to seven collimators that mainly generate beam loss signals. The sensors used were CsI + photomultiplier tube (PMT) and electron multiplier tube (EMT) and the data collection used White Rabbit (WR) and pico-scope to identify which collimator's sensor first signalled at the abort due to SBL. Figure 5 shows an example of those loss monitor signals and timing at each sensor section. Data analysis revealed that the beam loss mainly started at the D06V1 collimator. This collimator is located downstream of the beam injection section and has a narrow aperture to suppress background to Belle-II detector. However, when the D6 collimator was damaged and the aperture was widened, beam loss began in the D2 collimator section near the IR, indicating that the starting point of beam loss depends on the tuning of the collimator and is not limited to a specific location.

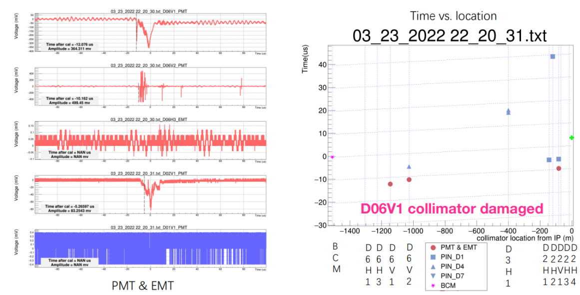

Figure 5: (Left) An example of the CsI and EMT, and EMT signal. (Right) The location of each loss monitors and the timing when the beam loss occurred.

We checked for beam size fluctuations as a cause of beam loss. SuperKEKB uses an X-ray monitor (XRM) to measure the beam size [9]. We have installed an ultrahigh speed CMOS camera in this XRM to take 1μs data at 100kHz when the abort is triggered. There was no sign of a significant change in beam size before the SBL.

Pressure bursts have been observed all over the place and rarely occur in the same place except at the collimator section as shown in Fig.7. It may be the result of abort rather than the reason. However, as shown in Fig. 8, the pressure of D06H3 and H1 upstream of the D6 vertical collimator, where the aperture is narrow and losses often start first, shows curious behavior. Only in this collimator section is there a rapid or nonlinear increase depending on the beam current. The temperature near the collimator was also examined, but behavior appears normal.

Acoustic waves were detected during SBL at the collimator, but only a few events were measured before shutdown, so measurements will continue to demonstrate the fireball effect, which will be discussed later.

CANDIDATE REASONS FOR BEAM LOSS

No precursor phenomena such as beam oscillations, large orbital variations, size increases, or pressure bursts have been observed to be the cause of beam loss. There is also no evidence that the beam loss started at the same place or near the same place in the ring as the cause of the beam loss.

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One of the causes of beam loss seen in KEKB and other accelerators is damage to vacuum components such as RF fingers, in which case beam phase changes (beam energy loss) were observed from ms to several hundred μs before abort [10,11]. At that time, an anomalous temperature rise in the bellows chamber was observed and catastrophic damage to the RF fingers was observed, but such phenomena were not measured in this sudden beam loss. Beam loss due to dust was observed in the early stages of SuperKEKB operation [12,13,14]. However, when the vacuum chamber was cleaned and tapped to remove as much dust as possible, these events decreased.

Beam instability is not consistent with the cause of this sudden beam loss, since the growth time is on the order of tens of turns.

We considered the electron cloud effect in the collimator as a possible cause of SBL. In this case, SBL should be measured only in LER, but in SuperKEKB it is also measured in the HER beam, although the damage is smaller. Although no pressure bursts were observed in the SBL timing, curious behavior of the pressure in D06H3 may suggest that a discharge or electron cloud is occurring. According to simulations the electron density distribution changes with time. Immediately after the beam passes through the collimator, the electron density near the center is high, and 1 ns after the beam passes through, the electron density near the wall is high. But the maximum electron density is on the order of 1E13/ m^3 to 1E14 /m^3 and it is not sure how this relates to SBL.

Another hypothetical cause of the beam loss in a few turns is the "fireball" seen in RF cavities [15,16]. Particles with a high sublimation point are heated by the beam-induced field and become fireballs. When the fireball contacts a metal surface with a low sublimation point, a plasma is generated around the fireball. This plasma grows into a macroscopic vacuum arc and can interact significantly with the beam particles. The vacuum chamber is made of copper, which has a low sublimation point, whereas the collimator head is made of tungsten and tantalum, which have high sublimation points, and thus have the potential to become fireballs. This fireball hypothesis could explain SBL (~μs) due to the fast plasma evolution (~100 ns at the fastest).

CONCLUSION

One of the obstacles to increasing luminosity is sudden beam loss, the cause of which is still unknown. We have investigated it with loss monitors etc., and have been able to identify the point where the loss started, but have not found any phenomena that would elucidate the cause. D06H3 may cause beam loss due to dust or plasma, but there is no clear mechanism to cause SBL. Possible countermeasures include replacing the damaged head with a new one and applying an external magnetic field of 40 G or higher if EC is affecting. So far, the fireball hypothesis is the most promising hypothesis to explain the SBL. Future plans should include simulations of plasma and beam interactions. Monitoring will be enhanced to gather information. It is expected to be observed point-like acoustic sources in vacuum arcs by using acoustic sensors to prove the fireball hypothesis. Copper coating of collimator heads to prevent fireballs is also planned.

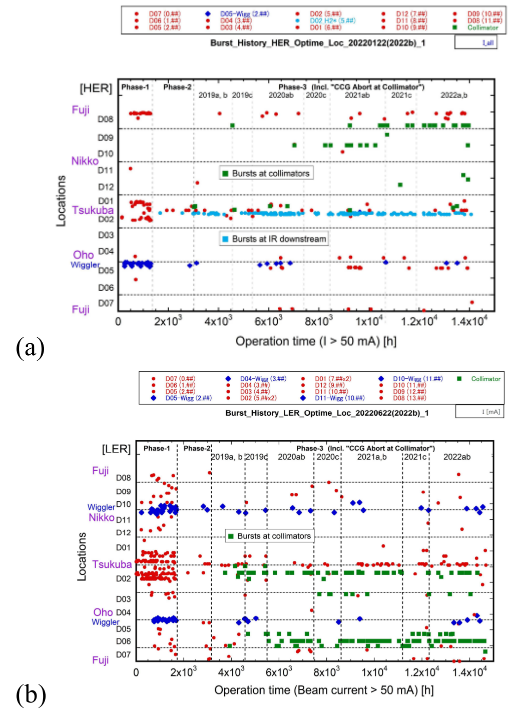

Figure 7: Pressure burst history at SuperKEKB HER (a) and LER (b).

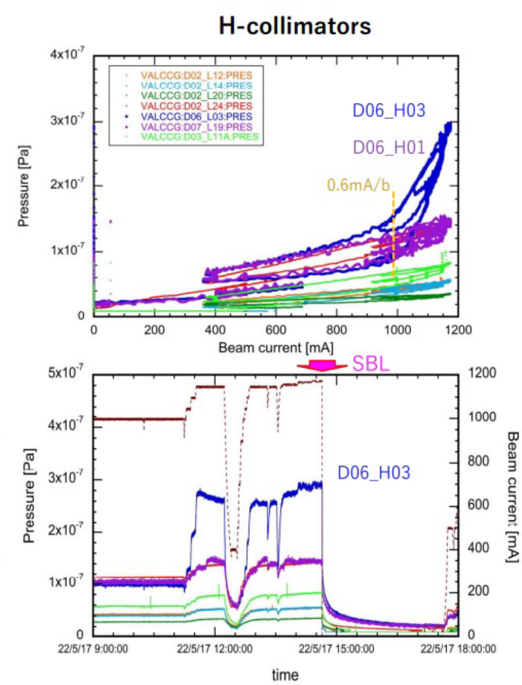

Figure 8: Current dependence(top) and time dependence (bottom) of the vacuum pressure in the collimator section when SBL occurs.

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REFERENCES

[1] Y. Funakoshi *et al*., "The SuperKEKB Has Broken the World Record of the Luminosity", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1-5. doi:10.18429/JACoW-IPAC2022-MOPLXGD1

[2] Y. Ohnishi, "Recent progress of SuperKEKB project and future prospect", in *Proc. IPAC'23*, Venice, Italy, May. 2023, paper TUOGB1, this conference.

[3] T. Mimashi et al., "SuperKEKB Beam abort System", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 116-118. doi:10.18429/JACoW-IPAC2014-MOPRO023

[4] T. Mimashi et al., "Performance of SuperKEKB High Energy Ring Beam Abort System", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2939-2942. doi:10.18429/JACoW-IPAC2017-WEPIK012

[5] H. Ikeda, T. Mimashi, S. Nakamura, T. Oki, and S. Sasaki, "Fast Trigger System for Beam Abort System in SuperKEKB", in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 754-756. doi:10.18429/JACoW-IPAC2022-MOPOMS048

[6] H. Ikeda, M. Arinaga, J. W. Flanagan, H. Fukuma, and M. Tobiyama, "Beam Loss Monitor at SuperKEKB", in *Proc. IBIC'14*, Monterey, CA, USA, Sep. 2014, paper TUPD22, pp. 459-462.

[7] M. Tobiyama *et al*., "Bunch by bunch feedback systems for SuperKEKB rings", in *Proceedings of PASJ2016*, Chiba, Japan, 2016, paper TUOM06.

[8] Y. Liu *et al*., "Study of beam loss of SuperKEKB based on new loss monitor system for Belle II", presented in JPS2022, Okayama, Japan, Sep. 2022.

[9] E. Mulyani, J. W. Flanagan, M. Tobiyama, H. Fukuma, H. Ikeda, and G. Mitsuka, "First measurements of the vertical beam size with an X-ray beam size monitor in SuperKEKB rings", *Nucl. Instrum. Methods Phys. Res. A*, vol. no. 919, pp. 1-15.

[10] Y. Suetsugu, "Experiences on High Current", presented in the 9th KEKB Acc. Review, KEK, February 16-18, 2004, https://www-kekb.kek.jp/MAC/2004/

[11] Y. Funakoshi, "KEKB status", presented in the 9th KEKB Acc. Review, KEK, March 21-23, 2006, https://www-kekb.kek.jp/MAC/2006/

[12] Y. Suetsugu *et al*., "First commissioning of the SuperKEKB vacuum system", *PHYSICAL REVIEW AC-CELERATORS AND BEAMS*, vol. 19, p. 121001, 2016. doi: 10.1103/PhysRevAccelBeams.19.121001

[13] Y. Suetsugu *et al*., "SuperKEKB main ring vacuum system status until the end of Phase-2 commissioning", *Journal of Vacuum Science & Technology A*, vol. 37, p. 021602, 2019. doi:10.1116/1.5083928

[14] S. Terui *et al*., "Observation of Pressure Bursts in the SuperKEKB Positron Ring", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2830-2832. doi:10.18429/JACoW-IPAC2018-WEPML058

[15] T. Abe, "Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities", KEK Accl. Lab. Topics, 2019. https://www2.kek.jp/accl/eng/topics/topics190122.html

[16] T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi and K. Yoshino, "Direct observation of breakdown trigger seeds in a normal-conducting rf accelerating cavity", *Phys. Rev. Accel. Beams* vol. 21, no.12, p. 122002, 2018. doi:10.1103/PhysRevAccelBeams.21.122002