ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

SuperKEKB BEAM INSTABILITIES CHALLENGES AND EXPERIENCE

H. Ikeda*[1,2], H. Fukuma[1], T. Kobayashi[1,2], T. Mimashi[1,2], T. Mitsuhashi[1], G. Mitsuka[1,2], S. Sasaki[1], M. Tobiyama[1,2]
[1] High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
[2] SOKENDAI, Tsukuba, Japan

Abstract

KEKB was upgraded from 2011 over 5 years in order to increase the luminosity and started SuperKEKB commissioning in 2018 after the test operation. In order to cope with large beam currents and small beam sizes, various updates have been applied to the beam instrumentation system. This talk summarizes the performance of beam instrumentation in SuperKEKB Phase-III and challenges to it.

INTRODUCTION

SuperKEKB is a collider with 7 GeV electrons (HER) and 4 GeV positrons (LER). The circumference of the ring is 3 km and many beam instrumentation system are installed as shown in Table 1 [1]. Aiming at the world's highest luminosity, we adopted the nanobeam method. Therefore, as design values, we adopted a squeeze of βy* by 20 and a beam current by 2 relative to KEKB ones, and recorded a peak luminosity two times larger than KEKB [2]. Among various improvements related to beam monitors to get higher luminosity, we will focus on improvements related to synchrotron radiation monitors (SRM) and beam loss monitors (LM) in this paper.

SYNCHROTRON RADIATION MONITOR

We use emission-light from the bending magnet that located last part of the arc section of electron and positron rings. An extraction chamber is set at 23 m downstream of the source bending magnet. A diamond mirror is inserted in the chamber as shown in Fig.1. The emission-light is sent through an optical window and several transfer mirrors to an optical hut for various measurements.

We replaced the extraction mirrors for better measurements, and introduced a coronagraph for beam halo measurements and an injection beam measurement system using the same optics system as the coronagraph.

Diamond Mirror

An extraction mirror of visible light is made of diamond to suppress the thermal deformation. We developed a single crystal diamond mirror and made efforts to suppress the current dependence of thermal deformation, but the mirror had not only the current dependence of the deformation at high currents, but also some deformations made during manufacturing process at the beginning of SuperKEKB [3]. We made a new thick polycrystalline diamond mirror that is not easily deformed by heat, then installed it in 2020 [4].

Resistance to thermal deformation of the new mirror is similar to single crystal and its reflectance is high because the coating is changed from gold to platinum. As the result, we succeeded to obtain a sufficient amount of light for beam profile measurement of each bunch, and it became possible to measure the beam halo and injection beam for each turn.

Table 1: SuperKEKB Beam Instrumentation System

System	Quantity		
	HER	LER	DR
Beam position monitor (BPM)	466	444	83
Displacement sensor	110	108	0
Transverse bunch feedback system	2	2	1
Longitudinal bunch feedback system	0	1	0
Visible SR size monitor	1	1	1
X-ray size monitor	1	1	0
Beamstrahlung monitor	1	1	0
Betatron tune monitor	2	2	1
Beam loss monitor		207	34
DCCT	1	1	1
CT	1	1	0
Bunch current monitor	1	1	1

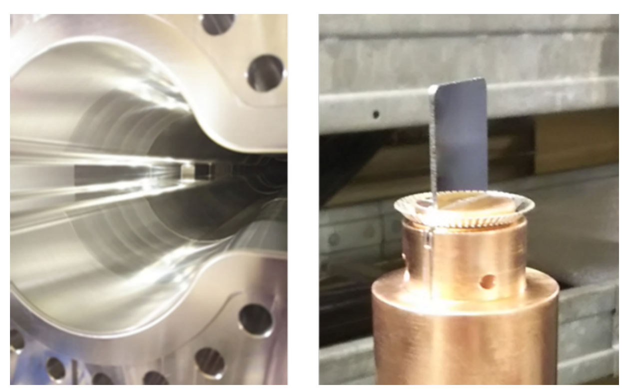

Figure 1: Extraction chamber (left) and Diamond mirror (right).

Coronagraph

Beam halo may cause unexpected beam loss or long-term irradiation leading to luminosity degradation and damage to accelerator components. Understanding and hopefully lowering beam halos have been attempted in

* hitomi.ikeda@kek.jp

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

high-power and/or high-luminosity accelerators. Our challenge is non-invasive measurements of beam halo with sensitivity better than 1e-5. Thus the coronagraph was introduced to SRM for that purpose [5]. Figure 2 shows the schematic view of the coronagraph. In order to eliminate chromatic aberration, the objective lens system adopts a reflective mirror system rather than a refractive lens system. An opaque disk was inserted to hide beam core and second stage was set as re-diffraction. Diffraction fringes of objective lens aperture is shown in Fig. 3. After blocking the diffraction fringes by the Lyot stop, we can observe the beam halo. Figure 4 shows the image of beam core, diffraction fringes and the re-diffraction fringes blocked by Lyot stop measured by a gated camera. Figure 5 shows the bunch current dependence of HER beam. Some parts look particularly bright because the center of the opaque disk and the center of the beam are not aligned due to changes of the beam orbit. Diffraction fringes made by the optics after the Lyot stop and leakage of diffraction fringes by the diamond mirror also remain. Figure 6 shows a comparison of halos between HER and LER with beam core shown overlapping. The halos look different although the measured beam current is a similar value.

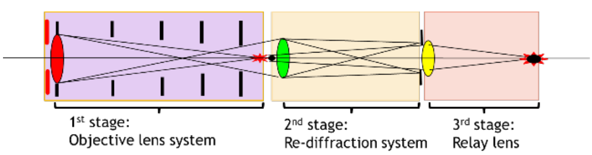

Figure 2: Schematic view of Coronagraph.

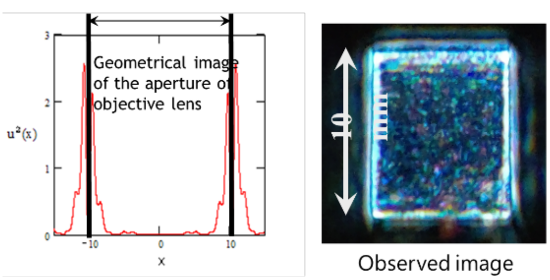

Figure 3: Left: Calculation of diffraction patterns. Right: The aperture images of the re-diffraction system.

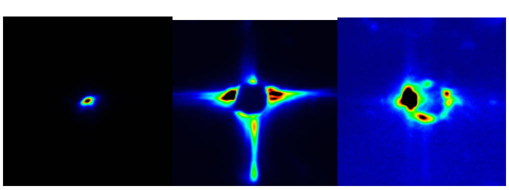

Figure 4 : Image of beam core (left), core blocked by a Φ 3 mm disk (center) and re-diffraction fringes blocked by the Lyot stop (right).

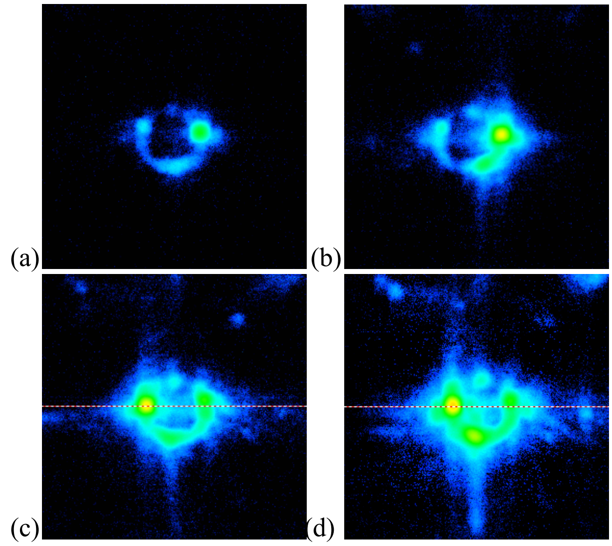

Figure 5: Bunch current dependence of re-diffraction image ((a) 0.055 mA/bunch, (b) 0.15 mA/bunch, (c) 0.28 mA/bunch and (d) 0.55 mA/bunch).

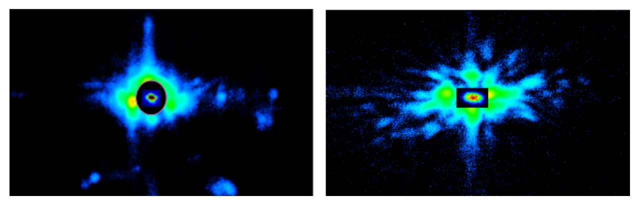

Figure 6: Comparison of halos between HER (left) and LER (right) with overlapped beam core.

The sensitivity in beam halo measurement was estimated to be order of 10^{-6} by measuring the brightness of the beam core and beam tail and scaling them with the current value used for the measurement.

Injection Beam Measurement

When the injection efficiency becomes unstable, it becomes difficult to accumulate the beam and the background to the Belle II detector increases, which interferes with physics experiments. It is important to observe how the injection beam circulates the ring usually and prepare for the measurement of difference with worth efficiency injection beam. Since it became possible to measure the beam in bunch by bunch, we tried to see the state of the injection beam. Object system designed for the coronagraph was used to measure the injection beam as shown in Fig. 7. Single-turn injection was applied to the HER beam. (Each injection kicks out the previously injected bunch. Then the ring always has only one bunch). We measured the beam shape in each turn after injection by using the gated camera.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

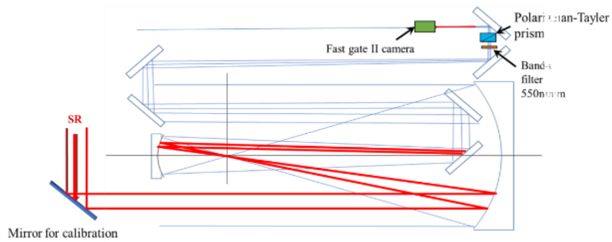

Figure 7: Gregorian objective for observation of injection beam f=7028 mm.

Calibration was performed using a stored beam reducing gate width of the gated camera when the beam was stable. The mirror was placed on a cross roller stage equipped with a micro-meter and moved horizontally by ± 15 mm to change the position on the screen. This movement corresponds to moving the beam virtually. The result is shown in Fig. 8. The error bars due to measurement re-producibility are smaller than the circles of the plot, and the variability of circles at the same position comes from the displacement of the beam due to the difference in measurement time. No large distortion is seen on the photoelectric surface of the CCD camera.

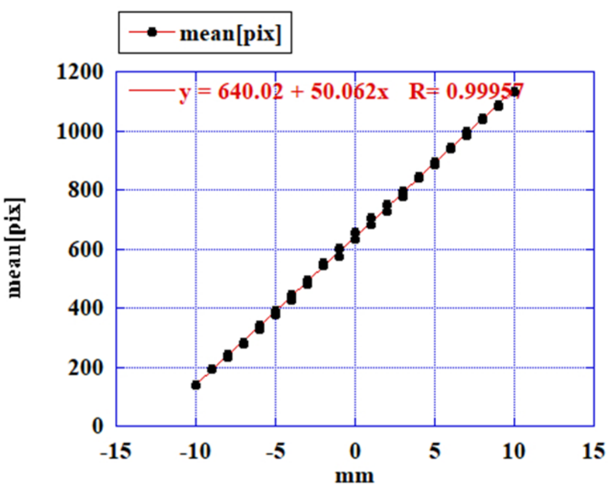

Figure 8: Calibration result of gated camera.

Horizontal beam size for each turn of the injection beam after the calibration is shown in Fig. 9 (a). The injection beam repeatedly expands and contracts and damped after 10,000 turns (10 ms). The beam size is including the diffraction effect in this measurement. Figure 9 (b), (c) show the injection beam oscillation. It can be seen that the amplitude becomes stable while oscillating with a width of about ± 4.5 mm at the maximum.

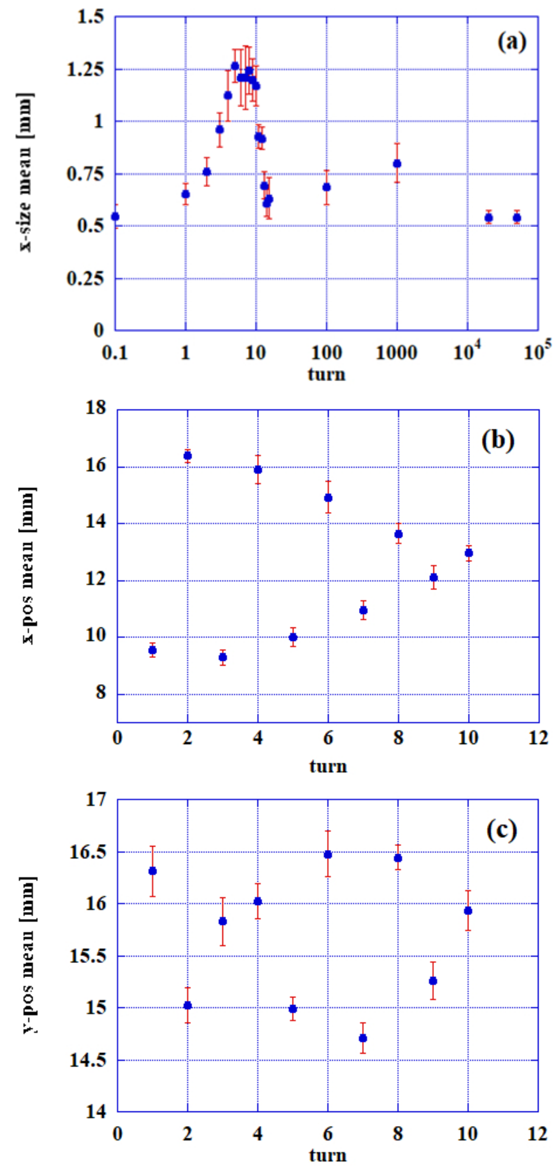

Figure 9: (a) Horizontal beam size, (b) horizontal beam position, (c) and vertical beam position for each turn after injection.

BEAM LOSS MONITOR

We have to protect the hardware components of the detector and the accelerator from the damage caused at high beam currents. The fast beam abort system is developed in the SuperKEKB in order to abort the beam as soon as possible when the abnormal situation happens. And also we need to investigate the cause of abnormalities in the beam and deal with them. In both cases, a combination of loss monitors and other monitors are important.

65th ICFA Adv. Beam Dyn. Workshop High Luminosity Circular e⁺e⁻ Colliders eeFACT2022, Frascati, Italy JACoW Publishing
ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

Loss Monitor System

Loss monitor (LM) measures the beam loss to be used for triggering the beam abort kicker, tuning and analysis of the beam operation [7]. We are using ion chambers (IC) and PIN photodiodes (PD) as a sensor. ICs are put to cable lacks of all over the tunnel to cover a wide range in space. PDs have fast response and can identify the ring in which the beam loss occurred. The PDs are mainly located downstream of collimators which have narrow apertures in the ring. LM signals from the whole ring are collected at five local control rooms (LCRs). Abort trigger signal is generated in integrators at LCRs and the generation time for beam abort is faster than 2 µs.

We have introduced optical fibers as a new loss monitor in order to deal with "sudden beam loss" which will be described later. Since the LM signal is sent to 5 LCRs around the ring, the cable length is not minimised. In order to send abort signals at the minimum distance, the optical fibers were laid in the power supply building closest to the downstream side of the collimator where beam loss is most often detected as shown in Fig. 10. The fiber is input to a PMT module and light is converted to electrical signals which generate an abort trigger signal. Figure 11 shows the signals from the fiber when the sudden beam loss occurred.

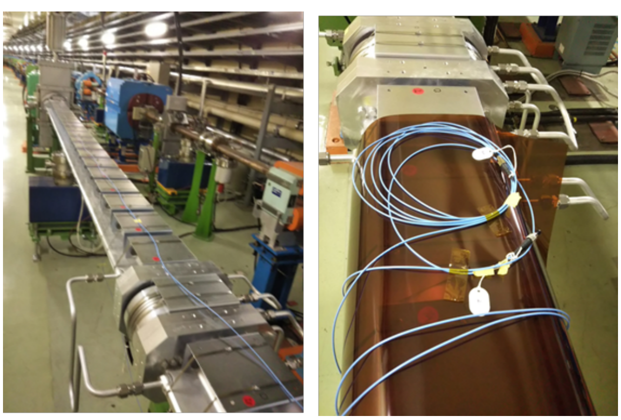

Figure 10: Optical fiber setting in the ring.

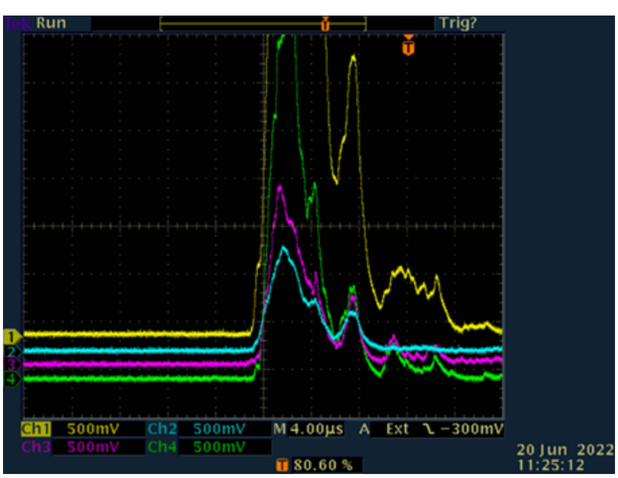

Figure 11: Signal of the optical fiber loss monitor.

Abort System

In order to protect the hardware components against the high beam currents, we installed the controlled abort system [8, 9]. The beam abort kicker consists of several magnets as shown in the Fig. 12. The beam is kicked by an abort kicker, taken out of the vacuum chamber through an abort window made of Ti, and led to a beam dump. Duration of dumped beam is 10µs which corresponds to one revolution time. Build-up time of the abort kicker magnet is 200 ns and we have to put empty bucket space (abort gap) larger than the built-up time. Synchronization of the kicker timing and the abort gap is required for the protection of hardware.

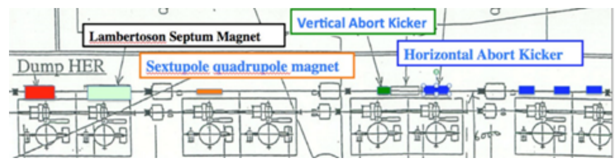

Figure 12: SuperKEKB abort kicker system.

Figure 13 shows the flow of time from the signal output of each trigger source to charging of the abort kicker and kicking all the beams out of the ring. We minimized the abort trigger time to protect the hardware damage as follows [10].

We introduced the injection veto system to PD LM to set lower threshold and for the abort trigger to be issued quickly. Also we changed the signal route of the LM installed at the downstream of one collimator that frequently issues abort triggers so as to send the abort trigger signal earlier. Since new fiber LM mentioned above is close to the abort kicker, it was a great time saver. In order to minimize delay to synchronize to the abort gap, unnecessary fixed delays were removed and the number of abort gap in the beam train was increased from one to two. As a result of reducing the time required in the abort system as much as possible, the delay time, which took 21 to 39 µs at the beginning of commissioning, was reduced to 17 to 30 µs.

Sudden Beam Loss

The biggest goal of SuperKEKB is to increase luminosity, but one of the obstacles is sudden beam loss. The cause of the sudden large beam loss is unclear, but it causes collimator (and other component) damage, QCS quench, large background to Belle-II. We also cannot storage a large current since it causes beam abort. Then we started a task force to investigate and resolve the cause of the sudden beam loss.

We checked the loss monitor signals at the abort occurred, which abort was thought to be caused by beam loss. The beam loss looks started within one turn at the collimators in whole ring and the Belle II detector We checked the loss monitor signals at the abort occurred, which abort was thought to be caused by beam loss. The beam loss looks started within one turn at the collimators in whole ring and the Belle II detector.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

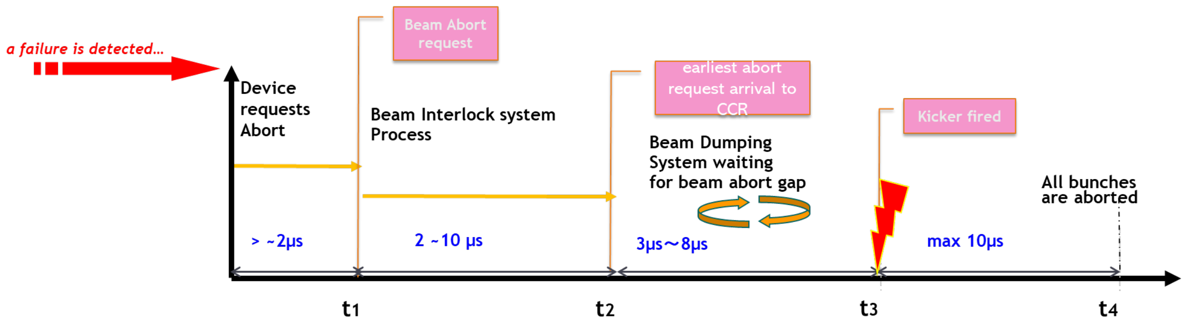

Figure 13: Time delay of the abort trigger flow.

In order to investigate where in the train the beam loss started at the moment of beam loss, we recorded the bunch current 4096 turns before the abort trigger using feedback processors [11]. Beam loss measured by the bunch current monitor (BCM) occurred suddenly on a certain turn as shown in Fig. 13. Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER. We don't know if it will happen even with a single beam operation, low current beam because we haven't operated for a long time. In order to find out where in the ring the beam loss first started, we installed loss monitors specialized for timing measurement inside the ring. Beam loss occurs in collimator and near interaction point, and where it occurs first depends on collimator tuning [12]. The Bunch oscillation is measured 4096 turns before the abort trigger using the feedback processors and the orbit is calculated from the data. The orbit changed on the order of 1mm at the feedback position. It is likely to occur when a bunch current is exceeded a level. The bunch current was around 0.7 mA at first, but after the collimator was damaged the current limit looks decrease. We checked many other monitors but there are no signs before beam loss starting such as small beam loss, beam oscillation, beam size change and it is not clear if the orbit changed significantly. Pressure bursts have been observed here and there, and it rarely occurs in the same place except in the collimator section. It may be the result of the abort, not the reason. Acoustic waves were detected at the time of collimator beam loss, but since we only measured a few events before shutdown, we will continue the measurements.

There is no evidence that the place where the beam loss first occurred is the same or close as the place where the causative phenomenon occurred. One of the causes of beam loss seen in KEKB and other accelerators is damage of vacuum component such as RF fingers in which case change of beam phase (beam energy losses) had been observed ms to hundreds of μs before aborts [13,14]. Abnormal temperature risings at bellows chambers had been observed and the catastrophic damages in the RF finger had been confirmed. It is proposed that the metal particles scattered by the arc discharge collided with the beam. Such a phenomenon could not be measured in this sudden beam loss. At the early stage of SuperKEKB, beam loss due to dust was observed [15-17]. However, after cleaning or tapping the vacuum chamber to remove as much dust as possible, the number of such events decreased. Since the growth time of conventional instabilities would be order of more than tens of turns, they do not match the cause of the current sudden beam loss.

A hypothesis that can cause the beam loss in a few turns is the "fireball" seen in RF cavities [18, 19]. A microparticle with a high sublimation point is heated by the beam-induced field and becomes fireball. Plasma is generated around the fireball after the fireball touches some metal surface with low sublimation point. The plasma grows up into a macroscopic vacuum arc, possibly leading to significant interactions with the beam particles.

We plan to continue discussions, including other possibilities and simulations.

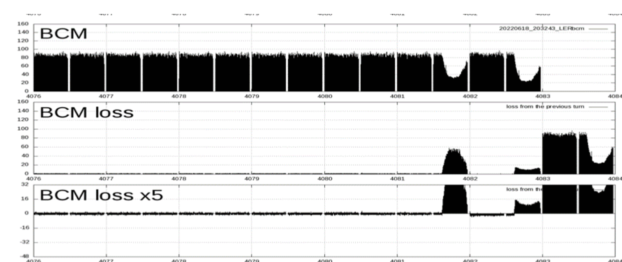

Figure 13: An example of a bunch current when a sudden beam loss occurs. First plot is a bunch current distribution, second plot is a bunch current difference from previous turn and third plot is 5 times of second plot.

CONCLUSION

By replacing the light extraction mirrors for both the electron ring and the positron ring, the image of the beam can be clearly focused, and the smaller charge beam can be measured turn by turn. We developed coronagraphs in SuperKEKB enabling non-invasive and high-sensitivity measurements for beam halo. Some beam halos are observed in both HER and LER and the sensitivity was ~O(1e-6) compared with the beam core. We also prepared a system for observing the behaviour of the injection beam in the ring when the injection efficiency becomes unstable. It was observed that the injection beam size was dumped while oscillating even when the beam condition was stable. The reference data was measured in the study mode, which can measure only the injection beam in a single turn injection and by masking the stored beam, it is

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAS0202

possible to measure some injection condition even during collision operation.

In order to protect the hardware from dangerous beam loss, we speeded up the abort trigger by increasing the number of abort gap, introducing injection veto for LM, changing the cable route and introducing new LM.

One of the obstacles for luminosity increasing is sudden beam loss and the cause of the beam loss is still unclear. We are investigating with loss monitors and other monitors, but no phenomena that clarify the cause have been found. We started the international task force to investigate and resolve the cause of the sudden beam loss.

REFERENCES

[1] "Beam Instrumentation", in SuperKEKB Design Report, 2014, https://www-linac.kek.jp/linac-com/report/skb-tdr/9_BeamInstrumentation2020_10_19.pdf

[2] 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

[3] J.W. Flanagan *et al*., "Thermal Performance of Diamond SR Extraction Mirrors for SuperKEKB", in *Proc. IBIC'19*, Malmo, Sweden, Sep. 2019, pp. 332-335. doi:10.18429/ JACoW-IBIC2019-TUPP01

[4] G. Mitsuka, H. Ikeda, and T. M. Mitsuhashi, "Renovation of the SR Beam Profile Monitors with Novel Polycrystalline Diamond Mirrors at the SuperKEKB Accelerator", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 313-315. doi:10.18429/JACoW-IPAC2022-MOPOPT031

[5] G. Mitsuka, H. Ikeda, and T. M. Mitsuhashi, "Design and Construction of Optical System of the Coronagraph for Beam Halo Observation in the SuperKEKB", in *Proc. IPAC'22,* Bangkok, Thailand, Jun. 2022, pp. 769-771. doi:10.18429/JACoW-IPAC2022-TUOXGD1

[6] H. Ikeda, T. M. Mitsuhashi, and G. Mitsuka, "Injection Beam Measurement Using Synchrotron Radiation Monitor at the SuperKEKB Electron Ring", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 3121-3123. doi:10.18429/JACoW-IPAC2022-FROXGD3

[7] 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.

[8] 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

[9] 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

[10] 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

[11] M. Tobiyama *et al.,* "Bunch by bunch feedback systems for SuperKEKB rings", in *Proc. of PASJ2016*, Chiba, Japan (2016), TUOM06.

[12] Y. Liu *et al.,* "Study of beam loss of SuperKEKB based on new loss monitor system for Belle II", presented at *JPS'22,* Okayama, Japan, Sep. 2022.

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

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

[15] Y. Suetsugu *et al*., "First commissioning of the SuperKEKB vacuum system", *Phys. Rev. Accel. Beams*, vol. 19, p. 121001, 2016. doi:10.1103/PhysRevAccelBeams.19.121001

[16] Y. Suetsugu *et al.,* "SuperKEKB main ring vacuum system status until the end of Phase-2 commissioning", *J. Vac. Sci. Technol., A*, vol. 37, p. 021602, 2019. doi:10.1116/1.5083928

[17] 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

[18] T. Abe, "Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities", *KEK Accelerator Laboratory Topics* 2019-01-22, 2019, https://www2.kek.jp/accl/eng/topics/topics190122.html

[19] T. Abe, T. Kageyama, H. Sakai, Y. Takeuchi and K. Yoshino, "Direct observation of breakdown trigger seeds in a nor-mal-conducting rf accelerating cavity", *Phys. Rev. Accel. Beams,* vol. 21, no.12, 122002, 2018. doi:10.1103/PhysRevAccelBeams.21.122002