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DEVELOPMENT OF BUNCH POSITION MONITORS TO OBSERVE SUDDEN BEAM LOSS OF SuperKEKB RINGS

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Abstract

In the SuperKEKB rings, we have encountered extremely fast beam losses occurring primarily within one to two turns in some parts of the bunch train. Such sudden beam loss induced severe failure in the vertical collimator heads, quenches on the superconducting final quadrupoles, and damage on the Belle II detector in some cases. It is essential to investigate the cause and take countermeasures. This paper presents the phenomena clarified by the bunch current and position monitor of the bunch feedback system. The upgrade plan for the existing monitor, and recently developed simple monitors installed in the suspected area is also introduced.

INTRODUCTION

The SuperKEKB collider consists of 7 GeV electrons (HER) and 4 GeV positron (LER) rings with the circumference of 3 km. To achieve much higher luminosity than previous KEKB collider, the nanobeam collision method was adopted with low emittance and low x-y coupling. Up to 2022b runs, new world record of highest luminosity of $4.7 \times 10^{34} \mathrm{cm}^2\mathrm{s}^{-1}$has been achieved with lower beam current than KEKB, with β_y*=1 mm which is much shorter than the natural bunch length of ~6 mm [1]. The beam currents were 1.3 A for LER and 1.1 A for HER with the stored number of bunches of 2249, which corresponds to almost 2 RF bucket filling pattern. The next target of the luminosity after the long shutdown 1 (LS1) form Jun 2022 to Dec 2023 is to increase the luminosity more than $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as soon as possible. During luminosity runs, we have encountered many so-called sudden beam loss (SBL) events on both ring which losses some part of bunch train within one or two turns when we have exceeded the bunch current of some threshold value (~0.65 mA for LER) [2]. The SBL usually damages the head of vertical beam collimators (and other accelerator components), quenches the final focusing superconducting magnets (QCSs), and causes huge backgrounds to Belle-II detector. Since the luminosity will be proportional to the bunch current product, those limitations on the bunch current are a big obstacle to achieve target luminosity. To understand the cause of SBL, and to take countermeasure to it, it is essential to monitor the beam behavior just before the SBL event, such as the bunch-by-bunch position and currents, the fastest beam loss points along the ring, vacuum burst if exist, etc.

We have used the bunch oscillation recorders (BORs) and bunch current monitors (BCMs) as the by-products of the bunch feedback systems installed in the ring to observe the SBL. Though the BORs and BCMs can separate the bunch information with the minimum bunch space of 2 ns, they have large limitations on such very quick event because of the location of the monitor is only one position per ring: it is impossible to estimate the cause point.

We have developed the simplified, low-cost BOR to place it in the suspicious point to observe the rough bunch oscillations and intensities. We are also trying to collect more detailed data by effectively using the existing system. The main parameters of the SuperKEKB rings on 2022b is shown in Table 1.

Table 1: Main Parameters of SuperKEKB in 2022b Runs

	HER	LER
Energy (GeV)	7	4
Circumference (m)	3016	
Maximum beam current (mA)	1099	1321
Max. bunch current (mA)	1	1.5
Natural bunch length (mm)	5	6
RF frequency (MHz)	508.886	
Harmonic number	5120	
Synchrotron Tune	0.028	0.024
Momentum compaction	0.00045	0.00032
L. damping time (ms)	29	23
Natural Emittance (nm)	4.6	3.2
Peak luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$4.7\mathrm{x}10^{34}$	
Bunch current monitor	1	1
Bunch oscillation monitors	3	3

SUDDEN BEAM LOSS

Monitors to Measure the Sudden Beam Loss

We have post-mortem monitor system to measure the bunch positions (x, y and longitudinal) and bunch intensity just before the beam abort event (BORs and BCM). As we use the same bunch position / intensity detector for the bunch feedback systems that down convert the $4 \times f_{RF}$=2 GHz components of the bunch signal, the outputs are proportional to both the bunch intensity and the bunch position distortion. The 18k10 digitizing board mainly consists of a fast 8-bit ADC (MAX108), a Spartan6 (XC6SLX45) daughter card with the form for a SO-DIMM card (Mars MX1) and VME-IF CPLDs [3]. They are mounted on a double width, 6U VME card. As we use the

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same RF signal (=509 MHz) as the ring to drive the ADC, the recorded information is completely synchronized to that from the bunch in the ring. During normal operation, those BORs and BCM are triggered by the quick intensity drop of DCCT such as beam abort event and record 4k turns before the trigger. The button electrodes for bunch feedback are placed in the Fuji straight section where almost no dispersion remains.

We have two sets of Libera Briiliance+ position detector per ring to also measure the post-mortem information in tern-by-turn mode, with roughly 90° of betatron phase advance at OHO straight section also with dispersion free. In LER, we also have another Libera Brilliance+ installed in the arc section with larger horizontal dispersion.

The beam loss monitor system is used to trigger the beam abort to protect the Belle II detectors and accelerator hardware. Ion chambers (ICs), PIN-photodiodes, and optical fiber systems are used as the beam loss monitoring sensors; most of the PINs are placed to the collimators of each ring to identify the ring where beam loss has occurred. ICs, on the other hand, are installed thought the tunnel and cover a larger space. Location of collimators are shown in Fig. 1. Normally it needs about 5-30 μs to abort the beam after the beam abort request.

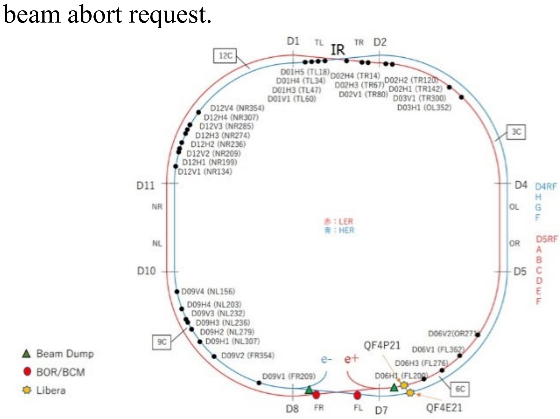

Figure 1: Location of the beam collimators of SuperKEKB ring.

Example of Sudden Beam Loss (SBL) Event

Figure 2 shows an example of the bunch current change for HER and LER, where the first row show the bunch current and the second row show the difference in bunch current from the previous turn 6-7 turns before the beam abort; this corresponds to the loss of the bunch current from the previous turn [3]. Part of the bunch train suddenly disappears just before the abort. Such beam losses had occurred in both HER and LER but SBLs in LER were much damaged the head of collimators, caused QCS quenches and damaged the inner-most detector of Belle-II. In the SBL of Fig. 2, the first and largest beam loss was recorded in the PIN diode around D6V1 vertical collimator but other PINs of collimators downstream of D6V1, optical fiber loss monitor around OHO straight section and Belle-II detector showed fast and significant beam loss [4].

Bunch oscillation from BORs have been measured simultaneously with the bunch current, the orbit can be estimated from the data. An example of the orbit behavior is shown in Fig. 3. Just before the beam loss begins, the orbit has slightly changed but the amount of change was small, on the order of 0.1 mm at the FB monitor. Even after the beam loss, the change in orbit was the order of 1 mm which might not be easy to explain the bunch loss with the excursion outside physical limit by the collimator.

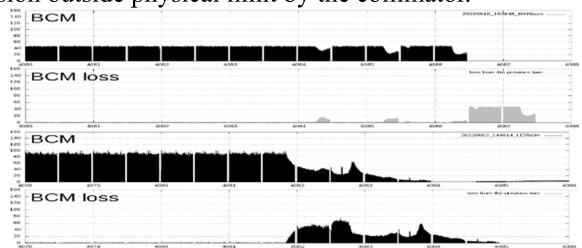

Figure 2: An example of the bunch current change of HER (upper) and LER (lower).

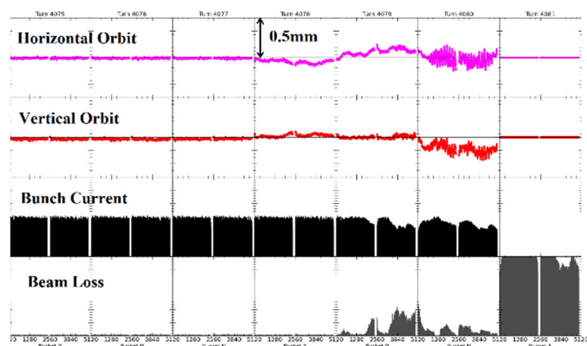

Figure 3: An example of bunch orbit variation and beam loss of LER.

We have also checked the post-mortem record (roughly 1 s before the abort) of the Libera using turn-by-turn mode. No significant orbit change was found in OHO and arc data. The beam size fluctuations just before SBL has been measured using an X-ray beam size monitor (XRM) with an ultrahigh speed CMOS camera to take 1 μs gate data at the revolution frequency of 99 kHz. Up to now no sign of a significant change in vertical beam size before the SBL has been observed. Vacuum pressure bursts have been observed all over the place and rarely repeat in the same section except at the collimators. Though some part of such vacuum burst might be the result of beam loss rather than the cause of the SBL, the collimator section, especially with damaged heads are still suspicious.

The known features of the SBL in LER are summarized as follows:

1. Some parts of the bunch train were lost in one or two turns without growth of oscillation: completely different from the normal coupled-bunch instabilities.
2. There appears to be a bunch current threshold (~0.65 mA/bunch) for the occurrence of SBL. The correlation with the total beam current appears to be rather weaker.
3. Beam loss mainly starts around D6V1 collimator where the effective vertical gap was the narrowest in the ring. There exist some SBL events which started D2V1 collimator when we occasionally operated the

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vertical gap of D6V1 larger due to the damaged heads of the collimator.

4. The BOR data have shown no significant beam excursion just before the SBL. It is strongly suspected that there was a strong kicking source between the Fuji-straight section and D6 arc section where first beam loss occurred.

Identifying the components where the beam is suddenly kicked is essential to understanding and taking countermeasure to the SBL.

UPGRADE PLAN FOR THE EXISTING BUNCH POSITION MONITORS

Since the BORs can record the position data in one location of the ring, it is essentially impossible to simultaneously determine the position and the beam divergence at that time. It is desirable to add the bunch position data with different betatron phase simultaneously.

In our transverse (horizontal and vertical) bunch feedback system, we have constructed two independent feedback loops in both HER and LER, with the betatron phase advance roughly 60 to 90 degrees at the monitor locations. The iGp12 digital filters [5] has two data acquisition functions; one with external SRAM of 12MB, which corresponds about 2.4 k turn of position data, and the other is the block memory (BRAM) in a FPGA. As the SRAM data is normally used to monitor the status of the feedback during operation, especially to check whether the feedback loop is clearly resistive or not, and also to perform the transient-domain measurements to estimate the unstable modes of coupled-bunch instabilities, it is not good idea to stop the automatic data acquisition and wait for the beam loss trigger. On the other hand, though the size of the block RAM is short, about 96 turns of data, it should work to get the real phase space information in the case of SBL. The EPICS software sequencer has been developed to monitor the second hardware trigger of iGp12s which is the same beam loss timing as the BOR trigger and transfer the BRAM data to the NAS. After the restart of the ring operation, the calibration data will be taken to get the fine conversion factor to the position.

SIMPLIFIED BUNCH OSCILLATION/INTENSITY MONITOR

To find the source point of the sudden beam kick, it is needed to spread the BOR like monitor before and after the suspicious components in the ring. Since the cutoff frequency of the vacuum chamber in the arc section is much lower (about 0.9 GHz) than that of bunch feedback section of Fuji straight section (about 2.8 GHz), we will not be able to use the same RF circuit of BOR as the bunch position detector. Moreover, the existing BOR system is too expensive and too complicated in setup at new location. During the operation of 2022b, we have tried to construct simplified bunch oscillation / intensity monitor system based using inexpensive 4-ch 2.5 GSPS digital oscilloscope of analog bandwidth of 1 GHz and connect it the existing BPM just before the D6V1 collimator. Figure 4 shows the block diagram of the system.

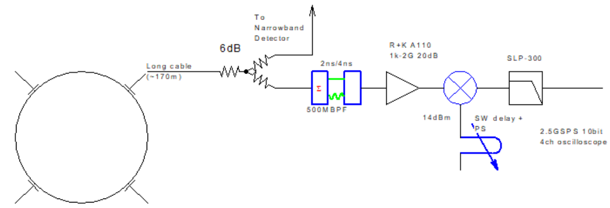

Figure 4: Block diagram of simplified BOR at 2022b.

We have split the existing BPM signal into two ways using 6 dB power splitters. 2-tap cable-type comb filters of 508 MHz were used to enhance f_{RF} component of the beam. Though the bunch signal separation less than 4 ns will be impossible due to the lower frequency detection, still the bunch position information could give us enough information on the source of the kick. The signal was down converted with the same RF signal and after the 300 MHz Bessel-type low pass filter (LPF), the detected signal was recorded by the digital oscilloscope. To rebuild the horizontal and vertical bunch position and intensity, off-line calculation process using 4-ch data has been prepared.

Unfortunately, this system did not work as expected. At first, as the isolation of double-balanced mixer and RF amplifier was not enough (about 70 dB), leaked LO signal had disturbed the narrowband detector. Moreover, we could not reconstruct the position data even with the known large bunch oscillation at the wrong injection time. On the other hand, the bunch intensity was almost successfully reconstructed.

We speculate that the reason for the poor reconstruction is the insufficient resolution (<10bit) of the oscilloscope. By employing RF hybrid circuit to subtract the analog signal before the oscilloscope, the position signal should have much better S/N.

We have developed the 509 MHz analog hybrid circuit which solve the signals of diagonal BPM, as shown in Fig. 5. The output of the hybrid will be directly sampled by the oscilloscope without analog down conversion. After data transfer to server CPU, the numerical I/Q detection will be done with off-line mode.

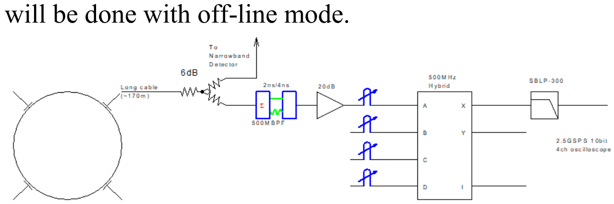

Figure 5: Simplified BOR with 508 MHz Hybrid.

The RF characteristics of the Hybrid has been tested using the network analyzer and the simulated BPM signal using the step recovery diode with 508 MHz comb filter. Figure 6 shows an example of measured S-parameter (A to sum port) and the time domain response (A to (A+B)-(C+D) port and C to (A+B)-(C+D) port). Excellent frequency and time response has been confirmed. Phase balances between the channels have also been checked and

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confirmed less than 3 degrees in the frequency range less than 1.2 GHz.

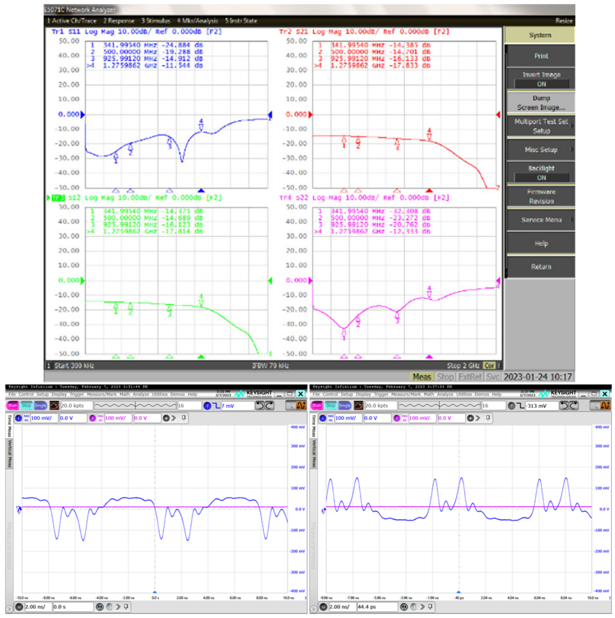

Figure 6: An example of frequency response (upper, A to sum port) and the time domain response (lower left, A to X, lower left A to Y).

The sampling rate of the oscilloscope will be reduced to 2.5 GSPS with the 4-ch operation mode. We have checked the response of the oscilloscope in the realistic configuration by changing the frequency and kind of low pass filter also using SRD signal. Figure 7 shows and example of the detected signal after Bessel type (933 MHz) LPF with 5 GSPS and 2.5 GSPS. In this case, it is impossible to reproduce the signal intensity with the 2.5 GSPS due to largely missing signal.

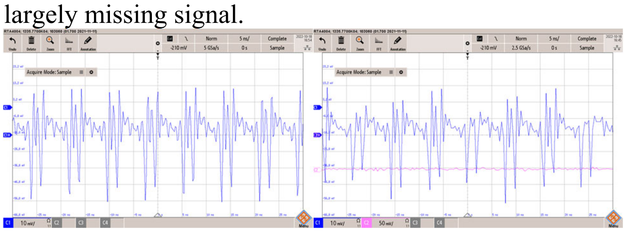

Figure 7: Example of the detected signal with 5 GSPS(left) and 2.5 GSPS(right).

To get equal response with the 2.5 GSPS mode, we will need to insert LPF with much lower cutoff frequency, say, less than 300 MHz. This also cause the signal separation between the bunches much challenging. Figure 8 shows an example of the signal with 300 MHz Bessel LPF, after numerical I/Q detection and digital LPF.

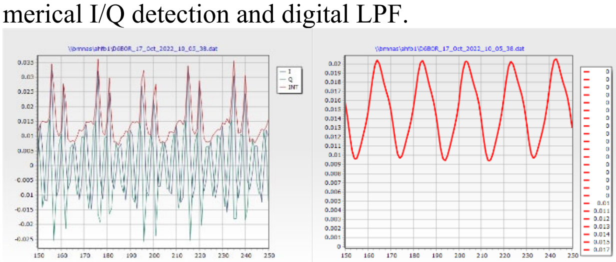

Figure 8: An example of the results of off-line analysis.

Another simple way to overcome this difficulty is, to prepare better oscilloscope which could sample all 4 channels with the sampling rate of 5 GSPS. We have obtained another new oscilloscope for the purpose and will use with much relaxed conditions for the LPFs. Currently, we are planning to install two system in LER, one on the same place as 2022b: upstream of the D6V1 collimator, and the other at the upstream of newly installed vertical collimator, D5V1 which will be configured to be the most effective collimator to cut beam halo.

The EPICS device support using socket connection, and the EPICS sequencer to transfer the data from the oscilloscope to the NAS has been ready and will be tested after the restart of the beam commissioning of LER on Dec, 2023.

SUMMARY

To investigate the cause of the sudden beam loss observed in SuperKEKB rings, we are preparing several kinds of post-mortem bunch position monitors which record the behavior of individual bunch positions and intensities over several turns just before the SBL event. For the rough bunch position and intensity detection around the suspected location in the ring, simplified bunch oscillation recorder based on the hybrid circuit and the digital oscilloscope. The required parameter on the cutoff frequency of the LPF and digital filter are also checked and are ready to test with the real beam.

The authors would like to express their sincere appreciation to the MDI colleagues who constructed and provided the ultra-fast loss monitor with fine timing base. They thank the commissioning group of SuperKEKB for their help and suggestions in the operation and machine development. This work is partly supported by the US-Japan collaboration in High Energy Physics (R&D for SuperKEKB and the next generation high luminosity colliders).

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