LONGITUDINAL BUNCH-BY-BUNCH FEEDBACK SYSTEMS FOR SuperKEKB LER

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Abstract

Longitudinal bunch-by-bunch feedback systems to suppress coupled bunch instabilities with minimum bunch spacing of 2 ns have been constructed in SuperKEKB LER. Through the grow-damp and excite-damp experiments with several filling patterns and the transient-domain analysis of unstable modes, the behaviors of possible impedance sources have been evaluated. The measured performance of the system, together with the performance of the related systems such as slow phase feedback to the reference RF clock are reported.

INTRODUCTION

The KEKB collider has been upgraded to the SuperKEKB collider with a final target of 40 times higher luminosity than that of KEKB. It consists of a 7 GeV high energy ring (HER, electrons) and a 4 GeV low energy ring (LER, positrons). About 2500 bunches per ring will be stored at total beam currents of 2.6 A (HER) and 3.6 A (LER) in the design goal. After the successful operation of phase-1 (without IR magnets), phase-2 (with superconducting final quadrupoles (QCSs) and Belle II detector but without inner-most sensors such as Pixel and SVDs), we have started the phase-3 operation with almost full-function of the Belle II detector from early March, 2019.

In the longitudinal plane, it is expected that the coupled-bunch instability (CBI) coming from the fundamental mode (-1, -2, and -3) will affect with medium beam current in both HER and LER. To cure the instability, the mode-by-mode feedback system in the LLRF [1] has been implemented. Growth time of other unstable modes from the imbalance in the HOM-cancelling in the cavities has been estimated slightly faster than the radiation damping time in LER with the maximum beam current of 3.6 A; 21 ms. At KEKB LER we did not need the longitudinal bunch feedback system up to the maximum beam current of 2 A. We are taking over the similar accelerating cavities (ARES) from KEKB so the threshold of the CBI is expected to be similar.

During the Phase-1 and Phase-2 operation, we have observed unexpected longitudinal coupled-bunch instabilities on LER starting much lower beam current, say, 600 mA. As the longitudinal motion strongly damage the luminosity in the collider, the suppression of the CBI is the must to get the higher luminosity.

We have prepared the longitudinal bunch-by-bunch feedback system (LFB) capable to handle the minimum bunch spacing of 2 ns in LER. The bunch feedback system consists of position detection systems, high-speed digital signal processing systems with a base clock of 509 MHz, and wide-band longitudinal kickers fed by wide-band, high-power amplifiers. We describe here the design, commissioning and the present status of our longitudinal bunch feedback systems. Table 1 shows the main parameters of SuperKEKB HER/LER achieved up to now.

Table 1: Main Parameters of SuperKEKB HER/LER in Phase 3 Operation

	HER	LER
Energy (GeV)	7	4
Circumference (m)	3016	
Maximum beam current (mA)	1010	870
Max. bunch current (mA)	1	1.5
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 ($cm^{-2}s^{-1}$)	$1.23x10^{34}$	
Bunch current monitor	1	1
Longitudinal bunch FB	0	1
No. of longitudinal kickers	0	4
No. of longitudinal amplifiers	0	8

OUTLINE OF LONGITUDINAL BUNCH FEEDBACK SYSTEM

Block diagram of the longitudinal bunch feedback system is shown in Fig. 1. All the transverse and longitudinal bunch feedback equipment including high-power amplifiers are installed in the Fuji straight section area [2].

Bunch Position Detector

The 2 GHz component of a bunch signal from button electrode is filtered using a comb-type bandpass filter,

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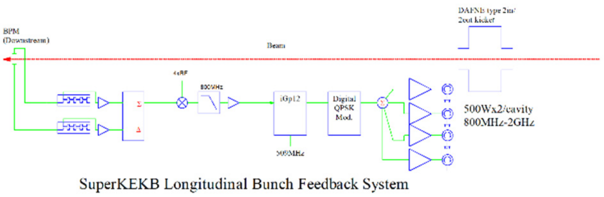

Figure 1: Block diagram of the longitudinal bunch feedback system in LER.

summed with timing adjusted, then down converted to a DC signal (relative phase) by mixing it with a signal of 4 times of RF frequency. We have used a DC amplifier after the Bessel-type low pass filter to suppress the large signal offset after the bunch train gap transient.

Digital Feedback Filter

The iGp12 [3] digital feedback filters have been used for signal processing of the bunch feedback system. The rejection of DC component including synchronus phase transient after the gap of the bunch train, adjustment of the feedback phase and one-turn delay and real-time diagnostics of the beam via grow-damp function and recordings of bunch positions have been realized with easy user interface. We have used the longest FIR filter available with the current firmware, 18-taps with the down-sampling factor of 3.

As the iGp12 has the fast signal monitor record, we have used the mean ADC value to estimate the relative phase from the beam to the RF master signal. We have made phase servo loop based on the software calculation. Though there is no longitudinal feedback kicker in HER, this phase servo has also been used.

Feedback Kicker

We have designed and installed four over-damped type longitudinal kickers (DAFNE-type kickers) in the LER, each with two input ports and two output ports with the center frequency of 2.25 × f_{RF}. Figure 2 shows the simulated S-parameter using HFSS [4] which shows the quality factor of around 5.

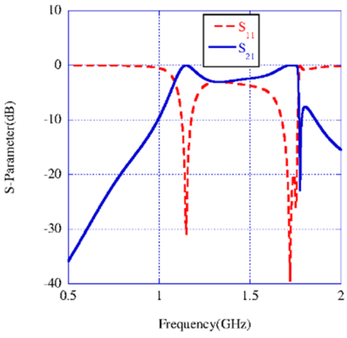

Figure 2: Simulated S-parameters of the longitudinal kicker.

The shunt impedance is also calculated by integrating the E-field obtained from HFSS simulation with properly taking into account the phase of the E-field. Example of calculated real part and imaginary part at the center frequency is shown in Fig. 3. In this case, the shunt impedance of 1.68 kΩ per cavity has been estimated.

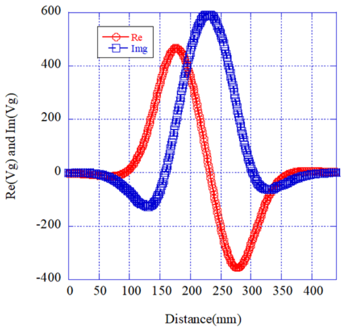

Figure 3: Real and imaginary part of the generated voltage at the center frequency, 1.15 GHz.

The trapped modes, longitudinal and transverse loss factor has also been calculated using GdfidL [5]. No severe trapped mode was found. Table 2 shows the basic parameter of the longitudinal kicker at the bunch length of 6 mm.

Table 2: Basic Parameters of the Longitudinal Feedback Kicker

Input / Output port	2/2
Center frequency	1.145 GHz
3 dB bandwidth	240 MHz
Shunt impedance	1.68 kΩ / Cavity
Longitudinal loss factor	0.406 V/pC / Cavity
Transverse kick factor	2.06 V/pC/m / Cavity
Length (flange-to-flange)	0.44 m

Backend Electronics and High-power Amplifiers

We need to modulate the carrier frequency of 1.15 GHz using QPSK modulator. We have developed the digital QPSK modulator which consists of the fast 4:1 switch and digital delay working with the RF clock. The baseband feedback signal from the iGp12 modulate the QSPK carrier with the amplitude-modulation using double-balanced mixer.

We have prepared two wideband UHF amplifier per cavity with saturated power of 500 W, R&K CA901M182K-5757R. The almost A-class configuration with modern FET and wideband combiner realizes the bandwidth of 900 MHz to 2000 MHz with gain flatness of less than 1.5 dB.

Unlike to the stripline kicker, the feedback kicker has no directivity between the input and output port so it is necessary to protect the amplifiers from the huge beam induced power. We have connected high-power absorptive low pass filter with the cut off frequency of 2 GHz to the input port of the cavity, then high-power wideband circulator with the pass band from 800 MHz to 2 GHz before the output of the final amplifier. Signal from one output port has been monitored using high-power attenuators with the power capacity of 1.5 kW. The power capacity except for the high-power attenuator is 5 kW. The temperature of most of the power components such as vacuum feedthrough, high power cables, and water-cooled load and attenuators have been monitored during the operation.

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP028

COMMISSIONING OF THE LONGITUDINAL FEEDBACK SYSTEM

Similar to the tuning of the transverse system, we have at first tuned the timing and phase of the bunch phase detector, ADC timing of the iGp12. The fine DAC timing within 2 ns of the iGp12 has been adjusted to synchronize the DAC output to the switch timing of the digital QPSK.

Unlike to the transverse bunch feedback system, the gain of the longitudinal bunch feedback system strongly depends on the kicker timing mainly due to much higher frequency of the carrier signal so we needed to adjust the timing with the precision of O(10 ps). After roughly adjusted the one-turn delay of the iGp12 by observing the feedback output and the beam induced output at the single-bunch condition, we have measured the open-loop beam response of the single-bunch longitudinal excitation at synchrotron frequency (*f*s) with the fine sweep of the kicker timing by changing the switch coaxial delay (COLBY step delay) [6]. Figure 4 shows an example of the peak and r.m.s. amplitude of the *f*s obtained by the iGp12 FFT function with one kicker (LK3). The feedback signal at the peak response (980 ps) appears roughly 1 ns before the beam-induced signal output as shown in Fig. 5.

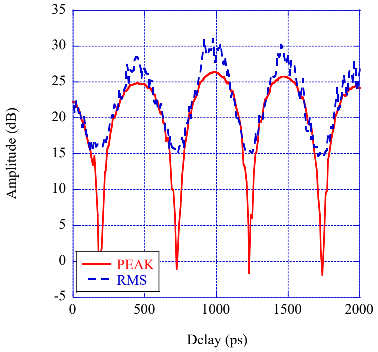

Figure 4: Beam response of the synchrotron frequency component with changing a kicker delay with 10 ps step.

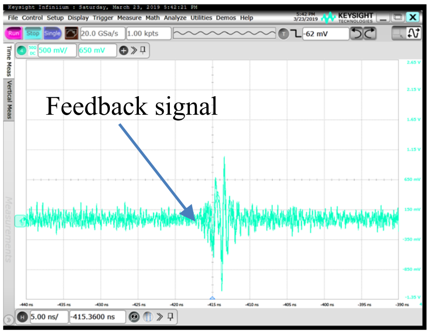

Figure 5: Example of the output of the feedback kicker with the beam at feedback delay setting of 980 ps.

Delay timings of the rest of three feedback kickers has been adjusted one-by-one to have the peak response of the excitation keeping the LK3 with the same timing.

Once feedback timing has been adjusted, we have closed the feedback loop to find the negative feedback condition by changing the feedback phase of the iGp12. The fine tuning has been performed using beam with excite-damp scheme. After turning on the LFB, we have observed the faster damp of the phase oscillation of the injected bunch from about 20 ms to 2 ~ 1 ms. Even without the spontaneous longitudinal CBI, the amplitude of the synchrotron oscillation has damped about 10 dB in normal operation.

LONGITUDINAL FEEDBACK EXPERIMENTS

During Phase-1 and Phase-2 operation, we have observed a longitudinal CBI. The threshold current strongly depends on the filling pattern; with by 2 filling, the CBI started around 150 mA with mode around -330, while in the by 3 filling pattern the threshold increased up to 800 mA. In addition, another set of unstable modes around mode -470 appeared with strong dependence of the gap width of the horizontal collimator nearest to interaction point D2H4. Such a case is shown in Fig. 6 with roughly 300 mA beam current with by 2 filling pattern, this mode and unstable motion is unexpected as the simulation showed no such longitudinal trapped mode at the collimator.

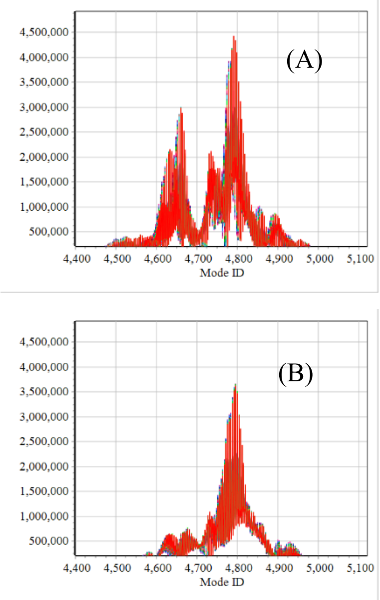

Figure 6: Unstable longitudinal modes with the half gap of horizonal collimator (D2H4) 13 mm (A) and 9.5 mm (B). Mode around -470 vanished with the narrower gap.

During Phase-3 operation, we have obtained dedicated study time to evaluate the performance of the LFB in several filling patterns (such as pure by2 and by3 patterns) with larger beam current than in the normal filling pattern (by 3.06). Figure 7 shows the longitudinal damping rate obtained via transient-domain analysis [7, 8] (excite-damp) at by 2 filling pattern, below the coupled-bunch instability threshold. Clearly, the damping rate shows linear dependence with the feedback gain.

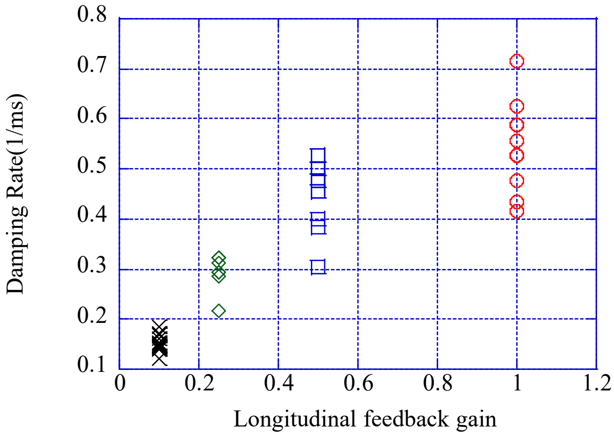

Figure 7: Change of the feedback damping rate with the feedback gain.

Though we have tried to observe the spontaneous CBI with increasing the beam current for each filling pattern, it was unsuccessful up to 500 mA (by 2) and 575 mA (by 3), except for the very slow growth of mode -1 with higher beam current. We therefore tried the excite-damp experiment. Examples of the excited modes and the grow-damp behavior of selected modes are shown in Fig. 8 and Fig. 9, respectively.

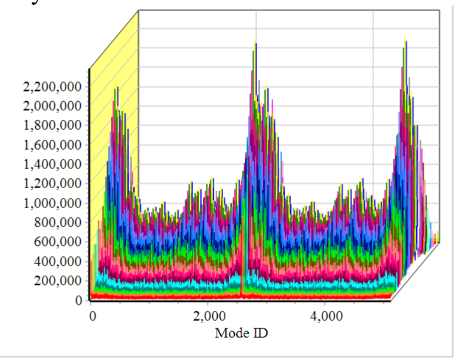

Figure 8: Example of excite-damp experiment with by 2 filling pattern, 500 mA. Depth axis corresponds the time evolution from 0 (Excite on) to 22 ms.

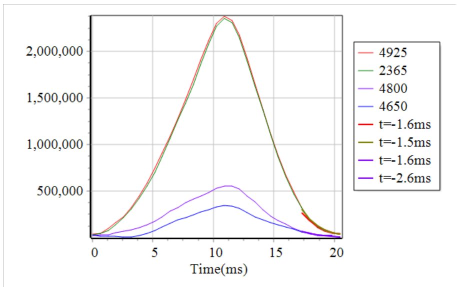

Figure 9: Example of transient behavior of some selected modes. The setting of digital filter has been flipped to positive feedback at t=0.5 ms, then restored to the negative feedback at t=12 ms. The results of the fitting with exponential curve are also shown.

As seen in Fig. 9, while the excitation and the feedback damp with small amplitude shows exponential response, the behavior with larger amplitude departs from exponential and reaches to almost linear. This behavior suggests feedback amplifiers easily saturate with the operational feedback gain. In this configuration the obtained damping rate around 0.5 / ms^{-1} fulfils the requirement for LFB in LER.

We have also tried to change the beam collimator (D2H4) with by 3 and by 2 filling patterns. Even with much larger beam current around 500 mA, we could not reproduce the CBI.

In the normal beam operation with beam collision, we have activated the LFB. Until the maximum beam current of 830 mA, no indication of longitudinal CBI. During the e-cloud study with much larger bunch current, around 1.5 mA/bunch with short bunch train, by 2 filling pattern, though we have observed slow longitudinal CBI other than the fundamental modes, it was completely suppressed with the LFB. The recapture of the feedback after grow-damp experiment was not difficult up to now.

SUMMARY

We have commissioned the longitudinal bunch-by-bunch feedback system in SuperKEKB LER. The damping rates achieved have been confirmed to scale linearly with the feedback gain. The longitudinal CBI observed during Phase-1 and Phase-2 operation was not reproduced in Phase-3 tests to date, but in all these tests the LFB system worked very well to stabilize the longitudinal motion during the colliding operation and the machine developments.

The authors would like to express their sincere appreciation to the commissioning group of SuperKEKB for their help in the operation and machine developments.

This work is partly supported by the US-Japan collaboration in High Energy Physic (R&D for SuperKEKB and the next generation high luminosity colliders).

REFERENCES

[1] K. Hirosawa *et al.*, in *Proc. LLRF2017*, `arXiv:1803.07677`

[2] M. Tobiyama *et al.*, in *Proc. PASJ2016*, Chiba, Japan, 2016.

[3] `http://www.dimtel.com/`

[4] ANSYS HFSS.

[5] `http://www.gdfidl.de/`

[6] `http://www.colbyinstruments.com/`

[7] J. D. Fox *et al.*, in *Proc. PAC'19*, New York, NY. p.636.

[8] M. Tobiyama *et al.*, Phys. Rev. ST Accl. Beams. 012801 (2006).