

## BUNCH BY BUNCH FEEDBACK SYSTEMS FOR SUPERKEKB RINGS

Makoto Tobiyama<sup>†</sup>, John W. Flanagan,

KEK Accelerator Laboratory, 1-1 Oho, Tsukuba 305-0801, Japan,

and Graduate University for Advanced Studies (SOKENDAI), 1-1, Oho, Tsukuba 305-0801, Japan

Alessandro Drago, INFN-LNF, Via Enrico Fermi 40-00044, Frascati(Roma), Italy

### Abstract

Bunch by bunch feedback systems for the SuperKEKB rings have been developed. Transverse and longitudinal bunch feedback systems brought up in very early stages of beam commissioning have shown excellent performance, and helped realize smooth beam storage and very quick vacuum scrubbing. Also, via grow-damp experiments and unstable mode analysis, they contributed to finding the possible source of an instability. The measured performance of the bunch feedback systems, together with the performance of the bunch feedback related systems such as the bunch current monitor and betatron tune monitor are reported.

### INTRODUCTION

The KEKB collider has been upgraded to the SuperKEKB collider with the final target of 40 times higher luminosity than that of KEKB. It consists of a 7 GeV high energy ring (HER, electron) and a 4 GeV low energy ring (LER, positron). 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. The main parameters of the Phase 1 operation of SuperKEKB HER/LER are shown in Table 1.

The first stage of the commissioning (Phase-1 operation) without the Belle2 detector started in Feb. 2016 and continued until the end of June. Even in the very early stage of the commissioning, we encountered very strong transverse coupled-bunch instabilities in both rings which limited the storable currents to very low values, less than 1 mA in multi-bunch operation in the case of HER. In the longitudinal plane, we have also encountered coupled-bunch instability around 660 mA in the LER, which was unexpected because we did not observe longitudinal coupled-bunch instability in the KEKB-LER up to its maximum beam current of around 2 A.

To cope with such coupled-bunch instabilities, we have also upgraded the bunch-by-bunch feedback systems, which were activated and tuned soon after observing the instabilities. We successfully suppressed the instabilities and increased the total beam currents. During the Phase-1 operation, we stored more than 1000 mA in the LER and 870 mA in the HER, with bunch spacings of 4 to 6 ns.

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 kickers fed by wide-band, high-power amplifiers. We describe here the progress and the present status of our feedback systems, with description of presumed instability sources

analysed by the unstable mode analysis with the grow-damp experiments. Also the related beam diagnostic tools such as the bunch current monitor, large scale memory board, will be shown.

Table1: Main Parameters of SuperKEKB HER/LER in Phase 1 Operation.

	HER	LER
Energy (GeV)	7	4
Circumference(m)	3016	
Max. Beam current (mA)	1010	870
Max. Number of bunches	2455	2363
Single bunch current (mA)	1.04	1.44
Min. bunch separation(ns)	4	
Bunch length (mm)	5	6
RF frequency (MHz)	508.887	
Harmonic number (h)	5120	
Betatron tune(H/V)	44.54/46.56	45.54/43.56
Synchrotron tune	0.02	0.018
T. rad. damping time (ms)	58	43
L. rad. damping time (ms)	29	22
x-y coupling (%)	0.27	0.28
Natural emittance (nm)	3.2	4.6
Max. injection rate (Hz)	50	50
$\beta_H/\beta_V$ at FB monitors(m)	13.4/29.7 5.5/6.2	19.4/20.0 19.4/20.0
$\beta_H/\beta_V$ at T-FB kickers(m)	21.6/11.5 17.2/15.5	23.4/9.9 21.9/15.9

### OUTLINE OF SUPERKEKB BUNCH FEEDBACK SYSTEMS

All of the feedback equipment is installed in the Fuji crossing area as shown in Fig. 1. There are two sections of position monitors in each ring. Stripline-type kickers for transverse deflection are installed upstream of the first monitor chamber. We use two transverse kickers with lengths of 41 cm. We have also installed two over-damped type longitudinal kickers (DAΦNE-type kickers) in the LER, each with two input ports and two output ports.

<sup>†</sup> email address makoto.tobiyama@kek.jp

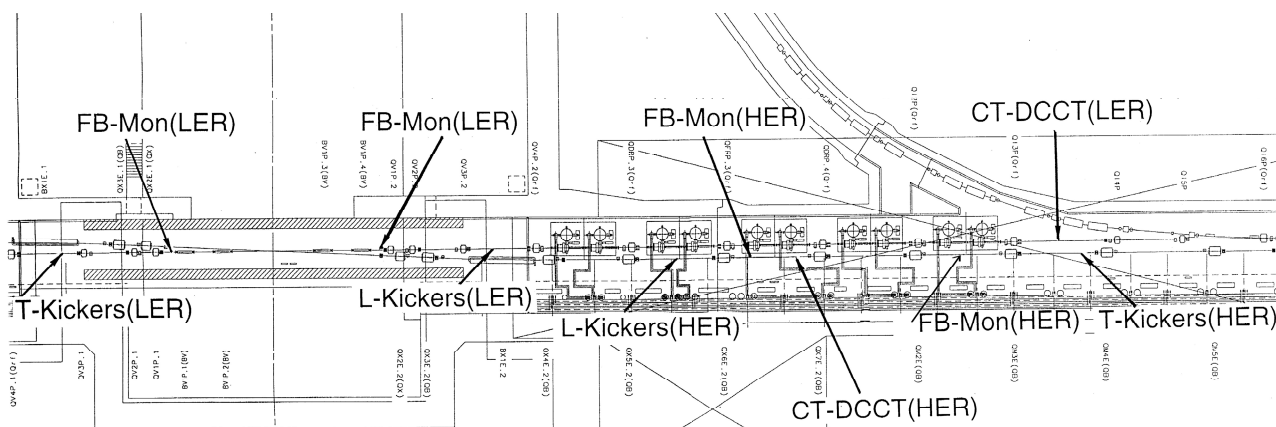


Figure 1: Location of the bunch feedback equipment at the Fuji crossing area. Positrons come from left side and electrons come from the right side. All the final feedback high-power amplifiers are installed under the crossing bridge.

Block diagram of the transverse and longitudinal bunch feedback system is shown in Fig. 2. Since the fractional part of the betatron tune on both horizontal and vertical planes may be very near to the half integer in order to maximize luminosity, we have prepared a double feedback loop in the transverse planes with a betatron phase advance between monitor chambers of around 90 degrees.

### Bunch Position Detector

We have installed two feedback monitor chambers per ring with 24-button electrodes using glass-type sealing for improved time response [1]. The 2 GHz component of a bunch signal is filtered using a comb-type bandpass filter, then down-converted to a DC signal after a 180-degree hybrid by mixing it with a signal of 4 times the RF frequency. Bunch-by-bunch residual DC offset is cancelled by adding the sum signal to cancel the offset. We have used a DC amplifier (THS4303 DC to 1.8 GHz) after the Bessel-type low pass filter to suppress the large signal offset after the bunch train gap transient.

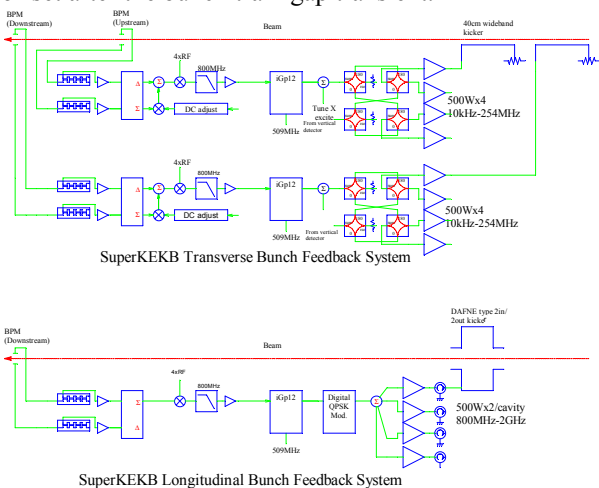


Figure 2: Block diagram of the transverse and longitudinal bunch feedback systems.

### Digital Feedback Filter

The iGp12 [2] digital feedback filters have been used for the signal processing of the bunch feedback systems.

The rejection of the DC component, adjustment of the feedback phase and one-turn delay and real-time diagnostics of the beam with grow-damp function have been realized. In total 9 processors (8 for transverse, 1 for longitudinal) have been used. Most of them have larger FPGAs (Xilinx XC5VSX95T) than in the normal iGp12 with XC5VSX50T, which enables longer FIR filters (20 Tap FIR with VSX95T, 12 Tap FIR with VSX50T). In addition, the new functions of single bunch beam transfer function measurement and PLL-based oscillation excitation have been implemented.

### High Power Amplifiers and Feedback Kickers

Two stripline-type kickers with lengths of 41 cm for transverse deflection are installed upstream of the feedback BPM block. Eight high power amplifiers with 500 W or 250 W maximum power (R&K, CA010K251-5757R and Amplifier Research, AR250A250 with bandwidth from 10 kHz to 254 MHz) are used to drive the kickers for each ring. As the four electrodes of the stripline kicker are placed at 45-degrees from the horizontal or vertical plane, we have developed an active hybrid to create mixed signals (H+V+, H+V-, H-V+ and H-V-) from the horizontal (H) and vertical (V) feedback signals by a combination of differential amplifiers (THS4509). At the upstream port of the transverse kicker, we have connected a high-power attenuator with a maximum power of 1.5 kW (Bird 1500-WA) to monitor the feedback signal.

For the longitudinal plane of the LER, we have installed over-damped cavity type (DAΦNE-type) longitudinal feedback kickers with the center frequency of 1145 MHz ( $=2.25 \times f_{RF}$ ), with calculated shunt impedance  $R_{sh} = 1.6 \text{ k}\Omega$  and a quality factor of around 5. The baseband feedback signal from the iGp12 processor is up-converted using the digital QPSK signal with the carrier frequency of 1.145 GHz, amplified with two 500W wideband amplifiers (R&K CA901M182-5757R) with the bandwidth from 800 MHz to 2 GHz. To protect the amplifiers from the huge beam induced power from the kicker, an absorptive type low pass filter ( $f_{cutoff} = 2 \text{ GHz}$ ) and a wideband circulator with bandwidth from 800 MHz to 2 GHz is inserted between the kicker and the amplifier. The tem-

peratures of most of the power components such as vacuum feedthroughs, high power cables, and attenuators have been monitored during operation.

### Feedback Related Instrumentation

By using the bunch feedback systems, we have prepared the following instrumentation: the bunch current monitor (BCM), the bunch oscillation recorder (BOR) and the betatron tune monitor. For the BCM and BOR, we have developed a large memory board for VMEbus board based on fast FPGA technology. It mainly consists of a fast 8-bit ADC, a Spartan6 daughter card and VME-IF CPLDs [3]. In the BCM mode, we limit the depth of the memory to up to one revolution of beam, and stop the recording with the injection trigger. The ADC data are also written to a reflective memory which share memory with other cards in the injection bucket selection system. The bucket selection system decides the next injection bucket, at the minimum bunch current, within the injection period of 20 ms. With this bunch current equalizer (BCE), very flat filling pattern have been achieved during the Phase-1 operation. Figure 3 shows an example of measured filling pattern of HER with 4 ns spacing.

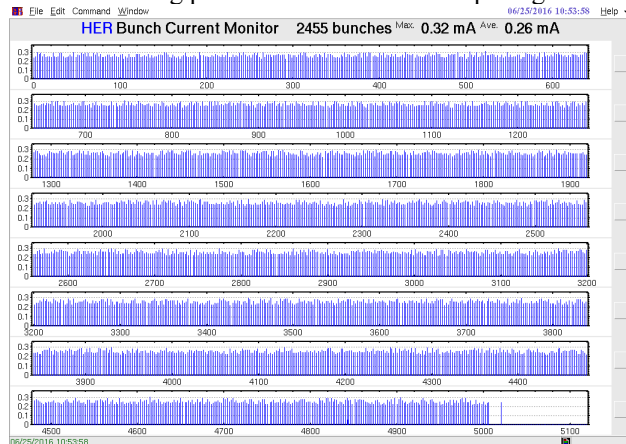


Figure 3: Example of bunch current of HER.

In the BOR mode, we could record the bunch oscillation signal using the same input as the iGp12s for up to 16k turns, which corresponds to 164 ms of revolution for all 5120 RF buckets. The data are transferred to a remote disk NSF mounted through a 10GbE network. Normally we used a beam loss trigger based on rapid change of the DCCT signal as the stop trigger for BORs. By analyzing the recorded data, we determine the cause of a beam abort or loss, and whether it was caused by beam instability or not.

For the betatron tune measurement, we prepared two types of systems: global tune measurement and single bunch measurement system. The global tune system excites all bunches using the bunch feedback kicker with low frequency down-converted from the tracking generator output of a spectrum analyzer (SA). An output of a feedback button electrode which is placed 45-deg. tilted from the horizontal plane is connected to the input of SA. The center frequency of the SA is set at the betatron frequency around 2 GHz. Though this simple sweeping

measurement works from very low current, say less than 1 mA, the response becomes wider and lower due to the feedback damping with the increase of the beam current.

In the single bunch measurement, we use an iGp12 to close the phase-locked loop excitation for a selected bunch without feedback damping. The betatron frequency is directly measured by the excitation frequency of the loop. Though it needs some tuning of the target frequency and phase of the loop, it works from very low bunch currents, around 0.2 mA, up to a maximum beam current greater than 1 A. Figure 4 shows an example of measured bunch current and betatron tune during operation.



Figure 4: Example of measured bunch current (upper) and the betatron tune with PLL method (lower).

## PERFORMANCE OF THE BUNCH FEEDBACK SYSTEMS

### Commissioning of the Bunch Feedback Systems

In the very early stage of the commissioning of both rings, we have encountered very strong transverse coupled-bunch instabilities which limit the maximum beam currents. We have roughly adjusted the feedback timing including one-turn delay, feedback gain and feedback phase by seeing the beam response on an oscilloscope, then closed one loop per plane on each ring. The instability was successfully suppressed and the beam current was increased fairly smoothly, which contributed greatly to vacuum scrubbing.

The feedback phase was adjusted in detail by observing the symmetry of the spectrum dip around the betatron frequency on the feedback signal in the iGp12s. If the feedback system is purely resistive, the spectrum becomes symmetric. In the case of some reactive feedback situation due to the disturbance by the beam optics or tune change, the dip becomes asymmetric reflecting the difference and the direction of the feedback phase from the purely resistive one. In the progress of optics correction of the rings, the optics group frequently changed both the operating points and the phase advances between the feedback monitors and feedback kickers. We therefore

corrected the phase of the digital filter after finding an asymmetry.

We have also tuned the second feedback loop after a month of operation of single-loop feedback and turned on both feedback loops simultaneously. The system worked fairly well with increased feedback damping, and without any difficulties.

During the scrubbing of the LER with a current of more than 660 mA, we encountered an unexpected longitudinal broadband coupled-bunch instability. We quickly tuned the longitudinal feedback system of LER. Though the fine tuning was not optimized, we successfully suppressed the instability up to the maximum beam current of the LER.

### Sensitivity and Dynamic Range of the Front-End

The original detector circuit was found to saturate at a bunch current larger than 0.5 mA in the operation of bunch current monitor. The feedback gain was also a little bit lower than expected. We therefore have modified the circuit to optimize the power level and have increased the total gain.

We measured the sensitivity of the feedback detection circuit using a single-bunched beam with bunch current of 0.3 mA by changing the closed orbit distortion (COD) at the feedback monitor. The result was about 580 counts/mm using the ADC counts of the iGp12. Since the resolution of the ADC of the iGp12 is 12 bits, it may saturate at a beam offset of around 0.7 mm with the design bunch current of 1.44 mA. As the offset could be adjusted by the offset cancelling circuit in the feedback detector remotely, and as the residual COD at the feedback detector is controlled with a continuous closed orbit correction system (CCC), the dynamic range is acceptable.

The longitudinal reference phase of the 2 GHz signal to the detector is automatically controlled through a slow feedback loop using the mean longitudinal position detected by an iGp12 (LER) or iGp (HER) to be constant throughout operation.

### Transient-Domain Analysis of Instabilities

The transient behaviour of the beam just after closing/opening of the feedback loop reveals many important characteristics of the coupled-bunch motions as well as the performance of the feedback systems [4,5]. The iGp12 has intrinsic functions to initiate and record the grow-damp measurement. Since we are using two iGp12s on one transverse plane, we triggered both iGp12s with a hardware line simultaneously.

Figure 5 shows an example of the evolution of unstable modes in a grow-damp experiment at the LER with a by-2 filling pattern where the total recording time, FB-off start and FB-off time are 24.72 ms, 2ms and 8ms, respectively. The unstable modes and exponential growth suggest this instability comes from electron-cloud instabilities.

In the HER, the growth time of the instability seemed to be governed by the vacuum condition, not only the mean vacuum pressure but also the worst vacuum pressure in the ring, especially around the wiggler section where very intense photons hit the new vacuum chambers.

Figure 6 shows an example of grow-damp experiment of vertical plane of HER. The growth behavior, which departs from exponential growth with large amplitude, suggests the instability is caused by ions, such as a fast ion instability.

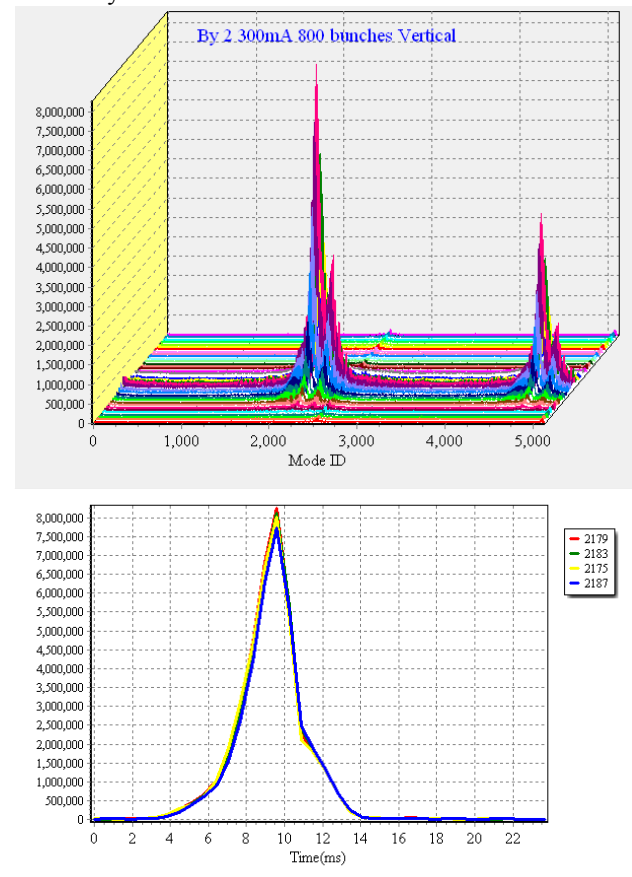


Figure 5: Evolution of vertical unstable modes with by-2 pattern in LER at a current of 300 mA. The growth time constant of mode 2179 was about 1.2 ms and the feedback damping time was about 1.1 ms.

In the longitudinal plane of the LER, we encountered a coupled-bunch instability when the beam current is larger than 660 mA in a by-3 filling pattern. The measured unstable modes are broad and spread around 2170 as shown in Fig. 7. Though the growth time was not so fast, we are investigating possible sources.

### Difficulties with Bunch Feedback Systems

During the operation of the bunch feedback and related systems, we encountered and solved several difficulties.

In the early stage of the commissioning, we occasionally injected into a single bunch more than 5 mA in the HER, despite a bunch current limit of less than 1 mA, which might cause great damage in the COD detectors. Upon inspection, we discovered saturation of the bunch current/feedback detection circuit, and modified the circuit to not saturate below 4 mA/bunch.

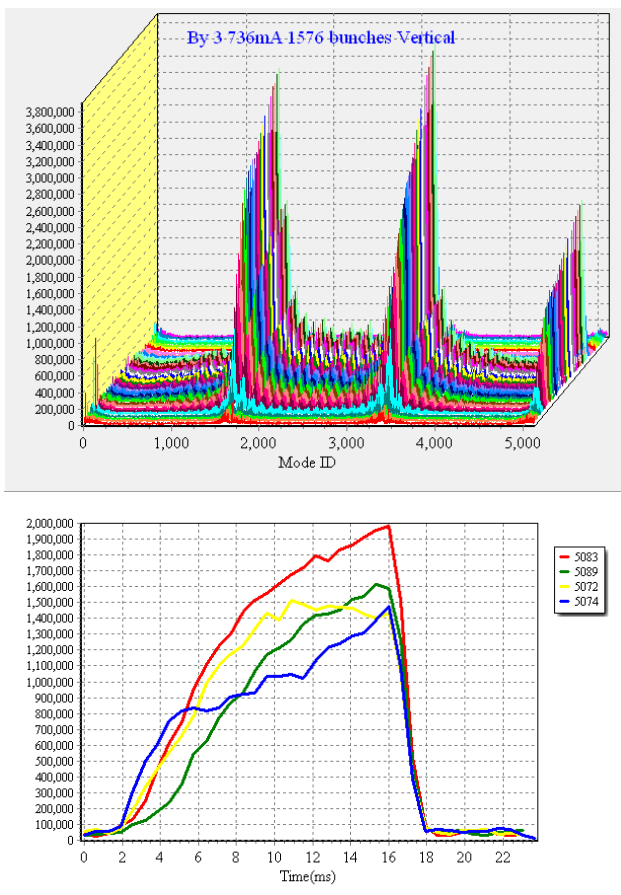


Figure 6: Evolution of vertical unstable modes with by-3 pattern in HER at current of 736 mA. The growth time constant of mode 5083 was about 1.2 ms, and the feedback damping time was about 0.6 ms.

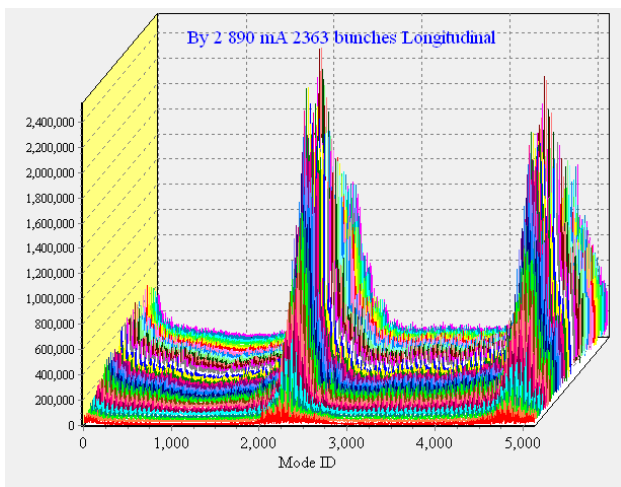


Figure 7: Evolution of longitudinal unstable mode with by-2 filling pattern in LER.

Though we monitored temperatures of feedback components in the beginning of commissioning, we did not implement an automatic beam abort request. On one occasion, due to an interlock in the external water chiller for longitudinal feedback components such as dummy loads,

circulators, and longitudinal kickers including high power feedthroughs, a very rapid increase in temperatures of the components occurred, which burned out all the water-cooling dummy loads. After this accident, we implemented a software based beam abort request based on checking the temperatures and the status of the water chiller.

During operation, we found an increase in the reflected power from several rods of the transverse feedback kickers, which might be the result of rod damage in the kicker. Since the feedback damping was sufficient in the Phase 1 operation, we temporarily changed the power line from amplifier to high power attenuator, and continued the operation. After the end of Phase-1 running we inspected all the components by TDR and found loosely connected N-connectors, and damaged high power attenuators. No suspicious symptoms have been found in the kicker and cables. Nevertheless, we are planning to open the kickers to check directly.

## SUMMARY

Bunch by bunch feedback system and related systems for SuperKEKB ring have been constructed and commissioned. Transverse and longitudinal bunch feedback systems were tuned and activated in the very early stage of the commissioning and have shown excellent performance, helping to realize smooth beam storage and very quick vacuum scrubbing. With the grow-damp experiments and their unstable mode analysis, they contributed to finding possible sources of instability.

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