Commissioning of the FPGA-based Transverse and Longitudinal Feedback System

Authors

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Multi-bunch instabilities may deteriorate beam quality, increase beam emittance, and even cause beam loss in the synchrotron light source. The feedback system is essential to suppress multi-bunch instabilities caused by the impedances of beam ducts, and trapped ions. A new Field-Programmable Gate Array (FPGA) based transverse and longitudinal bunch-by-bunch feedback system has been commissioned at the Taiwan Light Source (TLS). A single feedback loop is used to suppress the horizontal and vertical multi-bunch instabilities simultaneously. Longitudinal instabilities caused by cavity-like structures are suppressed by the longitudinal feedback loop. The same FPGA processor is employed in the transverse feedback and the longitudinal feedback system respectively. Diagnostic memory is included in the system to capture the bunch oscillation signal, which can be used to support various studies.

Two major upgrades of TLS have been completed recently - Superconducting RF cavity (SRF) in Dec. 2004 and the top-up operation mode in Oct. 2005. These upgrades are intended to increase the stored beam current, to eliminate strong instability caused by High-Order-Modes (HOM) from Doris cavities, and thereby maintain a constant heat load to provide higher quality photon beam. Transverse and longitudinal feedback loops are required to exploit the benefits of these upgrades. Transverse and longitudinal multi-bunch instability caused by the resistive wall, cavity-like structures of beam ducts, and ion effects are suppressed by using feedback systems. The transverse and longitudinal bunch-by-bunch feedback loops were developed in late 2005 and early 2006 respectively to ensure good quality beam for users.

Both transverse and longitudinal feedback system share the same architecture. The feedback processor used at TLS was originally developed at SPring-8. A highly flexible design of the feedback processor led to an easy adoption to TLS applications with minor modifications. The system consists of Beam Position Monitor (BPM), analog front-end (analog de-multiplexer for transverse feedback and phase detector for longitudinal feedback), a feedback processor, a Single-SideBand (SSB) or Quadrature Phase Shift Keying (QPSK) modulator for a longitudinal feedback system, power amplifiers and kickers as shown in Fig. 1. The signals measured by the BPM are processed by an analog front-end, converted into a baseband signals and fed to the digital feedback processor where the position or phase signal of each bunch is converted into digital form and filtered by the FIR filters to extract error signal. The kicker is driven by the filtered error signal to suppress the bunch motion. The latency of the system should be one or two revolution of the storage ring plus the signal delay between the BPM and the kicker for the transverse feedback case. The latency time of the feedback processor is around 300 nsec. A good frequency response of the FIR filter can be easily achieved by using a two-turn delay (800 nsec) in the transverse feedback loop.

The feedback processor has four parallel channels. Each channel has an Analog to Digital Converter (ADC) and a Finite Impulse Response (FIR) filter. A dynamic range of several mm is required to avoid saturation caused by orbit perturbation at injection, or by a large distortion of closed orbit. The 12-bit resolution ADC can fulfil the requirement of dynamic range without using a correlator (notch) filter. The RF frequency, f_{RF}, is 499.654 MHz and the harmonic number is 200. In the four-ADC mode, the feedback processor and ADCs are operated with a clock frequency of $f_{RF}/4$. The f_{RF} is selected as carrier frequency for the signal measured by BPM electrodes. The signal carrying frequency band of beam motion is from 1/2 f_{RF} to 3/2 f_{RF}. A two-dimensional transverse feedback is implemented by using the single loop scheme with 20 taps FIR filter. A maximum of 50-taps in the FIR filter are supported for the longitudinal feedback. Decimation is possible for the longitudinal feedback. Up to 32 sets of FIR filter coefficients can be stored internal register of FPGA and are selectable via a USB 2.0 interface or an external logic input. In the latter case, the switching speed is about 10 nsec. This function makes the system very flexible for the use in grow-damp experiments. Up to 256 ms of bunch oscillation data can be stored in the DDR memory for further analysis. The frequency multiplier supplies a Digital to Analog Converter (DAC) clock at the RF frequency with a cycle-to-cycle jitter of 50 ps from the ADC clock. The processor equipped with five DACs - four for the multiplexed FIR filter output and one for multiplexed raw ADC data are used for diagnostics and tuning. Adjusting the internal delay can control the latency of the multiplexed FIR filter output. Each DAC has complementary outputs. When several kicker electrodes are used for feedback, the delay and polarity of the individual kicker must be tuned. Using these output functions can easily perform such tuning process. A Compact Flash (CF) card is used as a booting device and stores configuration data of the feedback processor. The USB2.0 is provided to control the processor and transfer captured data. A device driver of the feedback processor for the Linux kernel 2.4 is developed and most functions are controllable. The control software from NSRRC and Matlab are installed in a Linux PC to provide a convenient environment for the interface of the feedback processor. Matlab scripts are used to control the accelerator through the existing Matlab interface, the feedback processor via the USB 2.0 interface, and electronic instruments via the IEEE-488 interface. This environment can support various request effectively in routine operation and accelerator studies.

The SRF upgrade reduces the bunch volume by increasing the RF gap voltage. Severe transverse instability cannot be suppressed by positive chromaticity in a manner that is convenient in routine operation. The resistive wall and ion-related effects might contribute to such instability. The old analog type transverse feedback system is highly sensitive to the choice of working tune. We adopt the new FPGA based two-

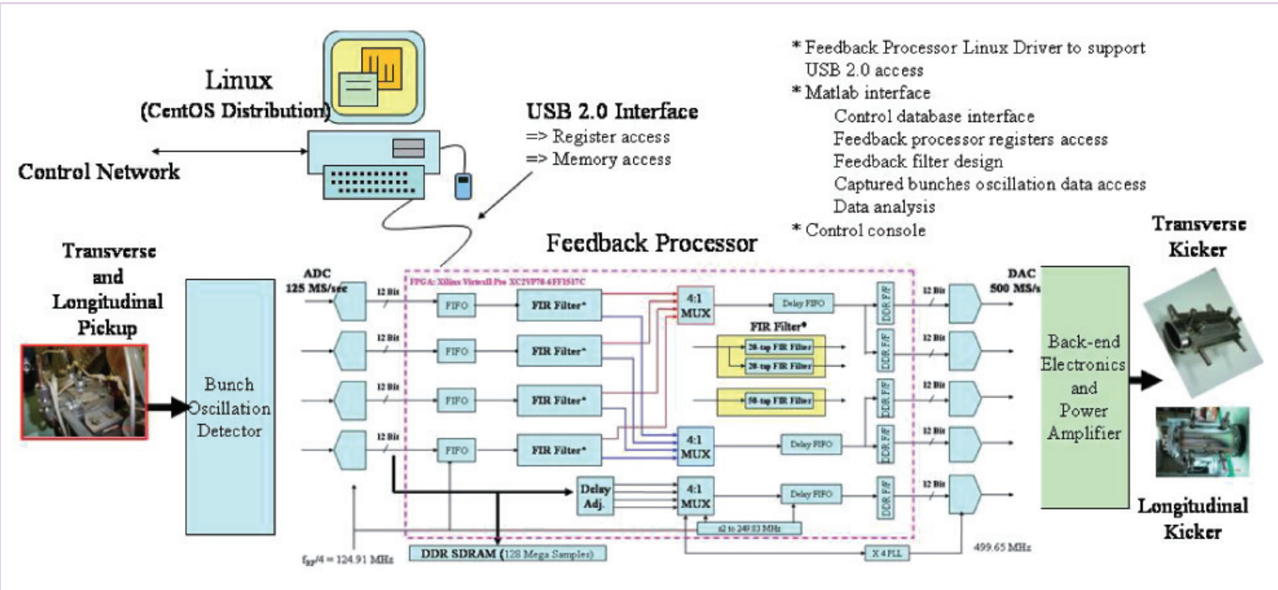


Fig. 1: Functional block diagram of the bunch-by-bunch transverse and longitudinal feedback system.

dimensional transverse feedback system with a single loop scheme. The transverse feedback loop consists of one pick-up and one kicker. The feedback FIR filter is linearly combined with vertical and horizontal responses. Bunch signals are multiplexed into four parallel channels in an analog manner. Delay lines align the four consecutive bunches in parallel sense. ADC with four parallel channels and four FIR filters are used to process the feedback signal. The differential output of the DACs drives two power amplifiers. Time domain least square fitting is applied to design the current configuration. The FIR filters are also compensated for the phase advance between the pick-ups and the kickers. Figure 2(a) shows numerous betatron sidebands without feedback. These betatron sidebands are fully suppressed by the feedback loop, as shown in Fig. 2(b). Figure 3 shows the results of model analysis in the typical vertical grow/damp data measurements. A damping time less than 1 msec at an operation current of 300 mA is achieved. Beam blowup dues to transverse instability with feedback off can be easily identified from the synchrotron radiation profile monitor as shown in Fig. 4(a). After the feedback loop is closed, the beam becomes stable, as shown in Fig. 4(b).

TLS has suffered from severe longitudinal instabilities during last decade. The HOM of two Doris cavities are the main source of these instabilities. A second tuner was introduced to adjust the HOM frequency in order to reduce the strength of instability. RF gap voltage modulation was adopted to alleviate the remaining instability at the cost of increased energy spread. Following the SRF upgrade, remained

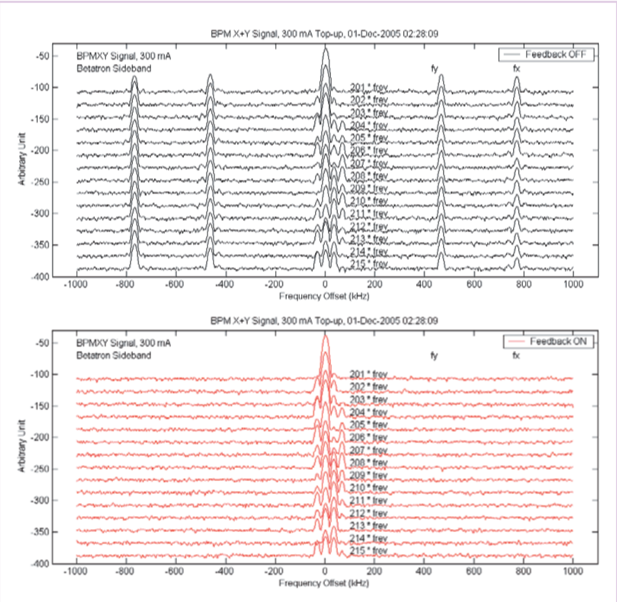


Fig. 2: Transverse spectrums form the harmonic of revolution frequency 201 to 215 without longitudinal feedback. Strong synchrotron sidebands are observed near the harmonics of the revolution frequency.

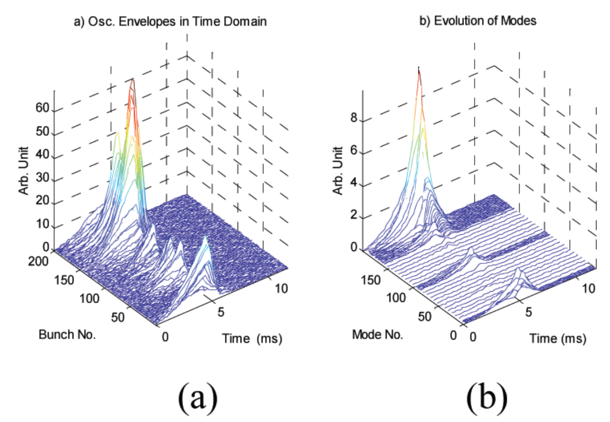


Fig. 3: The evolution of vertical oscillation envelops and modes in grow/damp experiments; (a) evolution of oscillation envelope of bunches and (b) evolution of modes.

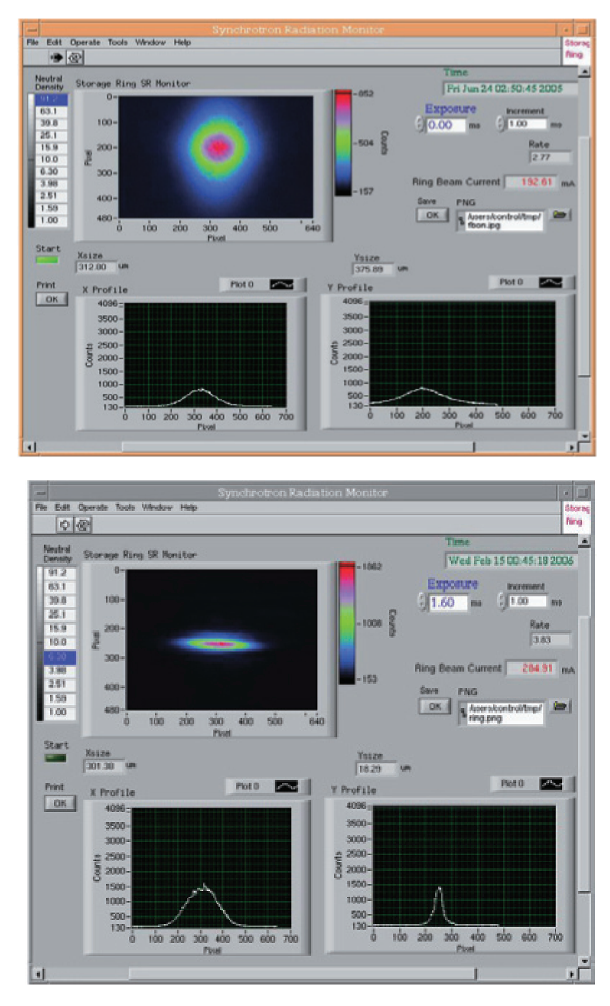


Fig. 4: The measured transverse profiles from the synchrotron radiation monitor.

longitudinal modes were caused by the impedance of beam ducts and unknown sources. Intensive studies were carried out during the operation of SRF in 2005. However, the source that caused these instabilities can not be identified yet. The longitudinal kicker based on the SLS design was modified with a beam tube fitted into the TLS vacuum chamber, which eliminates the need for a taper. The kicker was installed in January 2006. The longitudinal feedback system was commissioned in early February 2006. The BPM sum signals are fed into the RF front-end detector, which is used as a bunch-by-bunch phase detector working at 3 times of f_{RF} (1.5 GHz). The baseband output is split into four channels with proper delay to align signal of four consecutive bunches into four parallel channels at a data rate of 125 MHz. Those signals are fed into feedback processor subsequently. The digitized signals are filtered with 50-tap FIR filters. The corrected output is sent to the SSB modulator. The lower sideband is sent to the beam excitation amplifier and the kicker. The filter is designed with a typical method of FIR filter. Figure 5 shows the beam spectrum. The major longitudinal mode near 740 MHz is suppressed effectively by the feedback loop. A grow/damp experiment is also performed. Figure 6 shows the evolution of the envelopes and mode pattern. Figure 7 shows the measured beam profile of synchrotron radiation as the on/off effect of the feedback loop. Since the synchrotron radiation monitor is located in the dispersion region, the energy oscillation contributed significantly to the horizontal beam size. After the feedback loop is turned on, the horizontal beam size is drastically reduced. Figure 8 shows the image from streak camera without and with feedback. A large oscillation is observed without feedback. The energy oscillation is almost undetectable when the feedback loop is closed.

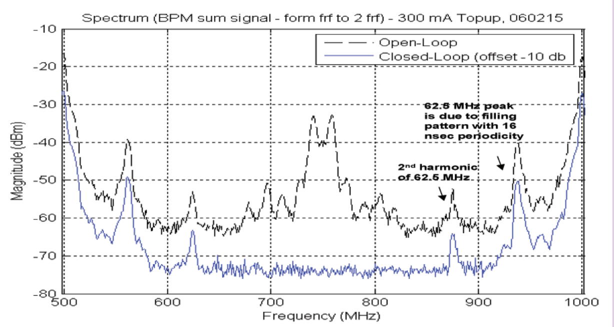


Fig. 5: Beam spectrum with and without longitudinal feedback loop.

This report summarizes the preliminary commission results of transverse and longitudinal feedback systems. Presently both feedback loops are in service

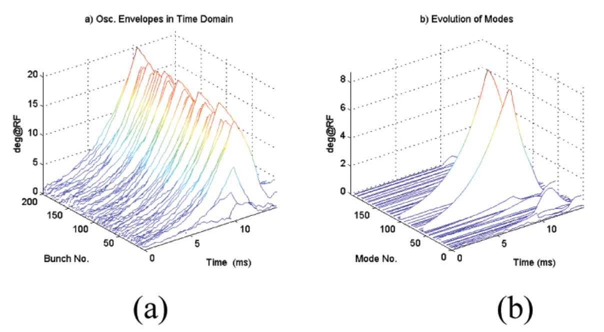
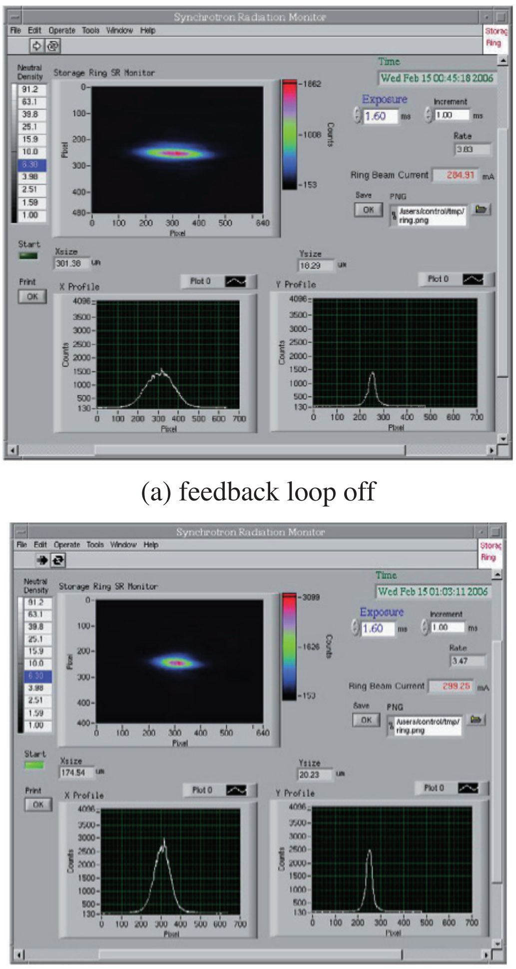


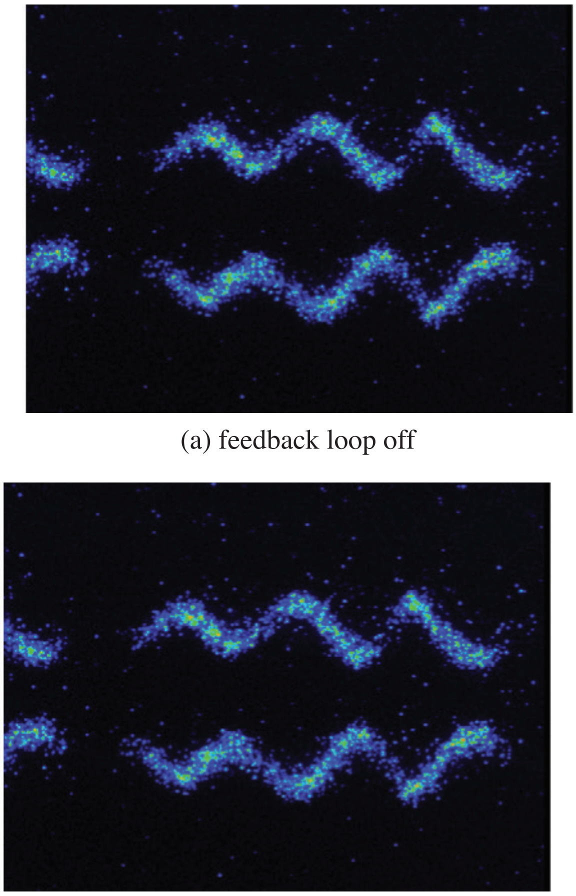
Fig. 6: Typical longitudinal grow/damp results. Only two modes are dominated; (a) evolution of oscillation envelop of bunches and (b) evolution of modes.



(a) feedback loop off

(b) feedback loop on

Fig. 7: Transverse beam profile with and without longitudinal feedback. Source point of the synchrotron radiation is in the dispersion region ($\eta \approx 0.108$ m). The horizontal beam size is effectively reduced by the longitudinal feedback loop.



(a) feedback loop off

(b) feedback loop on

Fig. 8: Snapshot of the one turn streak camera image. Vertical time span is 1.4 nsec, horizontal time span is 500 nsec in this dual scan configuration. The longitudinal feedback loop can effectively suppress the longitudinal motion.

during users' shifts. The transverse feedback system not only eliminates instability but also improves the injection efficiency since it enables near-zero chromaticity operation, which is essential for the top-up injection. Longitudinal feedback improves the performance of TLS. The system performance and reliability of both feedback loops are constantly being improved. The functionality of the feedback system will be gradually enhanced.

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