FPGA-BASED LONGITUDINAL BUNCH-BY-BUNCH FEEDBACK SYSTEM FOR TLS

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Abstract

An FPGA based longitudinal bunch-by-bunch feedback system for TLS was recently commissioned recently to suppress strong longitudinal oscillation. The system consists of pickup, a bunch oscillation detector and an FPGA based feedback processor borrowed form the design of SPring-8. Modulator converts the correction signal to the carrier frequency and the longitudinal kicker, which was re-designed from SLS' and works at 1374 MHz. The feedback processor is based upon latest generation FPGA feedback processor for processing bunch signals. The memory captures up to 250 msec of the bunch oscillation signal. The software and hardware design are also included for system diagnosis and to support various beam physics studies. Preliminary commission results will be summarized in this report.

INTRODUCTION

The Taiwan Light Source (TLS) of the NSRRC is a 1.5 GeV storage ring. Two major upgrades of TLS have been completed recently - the superconducting RF cavity (SRF) upgrade in late 2004 and the top-up operation in late 2005. Both upgrades are intended to increase the stored beam current from 200 mA to more than 400 mA, to eliminate strong high-order modes (HOM) instability caused from conventional RF cavities, and maintain a constant heat load, to provide high-quality photon beams. The multibunch feedback system is required to enhance the benefits of these upgrades. The HOM instability is a longitudinal couple-bunch instability caused by the cavity-like structure of the beam duct, can be suppress by using longitudinal multi-bunch feedback systems. The system was commissioned in early 2006. The status and preliminary results of the longitudinal feedback system are reported.

LONGITUDINAL FEEDBACK SYSTEM

TLS has suffered from severe longitudinal instability during the last decade. Two conventional RF cavities are mainly responsible for these HOM instabilities. The second tuner was introduced to adjust the HOM frequency to reduce the strength of the instability. RF gap voltage modulation [1] was adopted to eliminate the remaining instability at the cost of increased energy spread. Following the SRF upgrade, some residual longitudinal mode remained [2], perhaps because of the residual impedance of the beam ducts or some unknown

sources. An intensive investigation was conducted during the operation of SRF in 2005. However, the source of this instability remains unclear. The longitudinal feedback system is used to suppress remaining instability.

TABLE 1. Parameters of the longitudinal feedback system.

| Parameter	Value
Energy, E	1.5 GeV
RF frequency, f_{RF}	499.654 MHz
Harmonic number, h	200
Revolution frequency, f_{rev}	2.49827 MHz
Momentum compaction factor	0.00067
Operating current, I_b	300 mA (June 2006)
Synchrotron frequency, f_s	33.7 kHz
Synchrotron tune, v_s	0.0136
Down-sampling factor, D	4
Bunch sampling frequency, $f_{sampling}$	frev/4 = 625 kHz
Working frequency of the phase detector	3 f_{RF} (or 6 f_{RF})
Phase detector range	$\pm 30^o$ ($\pm 15^o$)
Taps of feedback FIR filter	up to 50
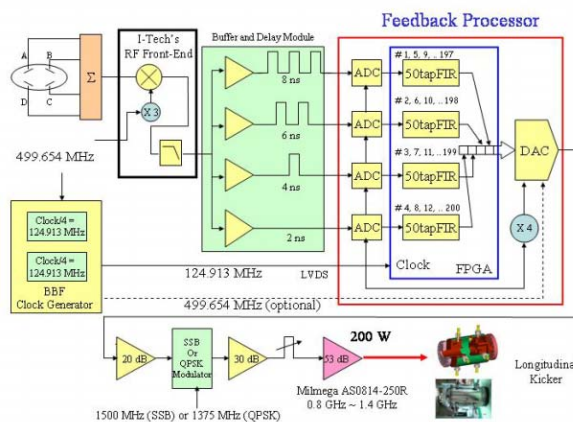
Figure 1. Functional block diagram of the longitudinal feedback system.

The longitudinal kicker that was based on the design of SLS with the modified beam tube to have the same cross section as the TLS vacuum chamber [3], to eliminate the need for a taper, given spatial limitations. The kicker was installed in January 2006. The longitudinal feedback system was commissioned in early February. The machine was started from cold after a long shutdown at that time. The FPGA feedback processor-key component of the feedback system for TLS was originally developed for the SPring-8 [4]. A highly flexible design of the feedback processor led to the easy adoption of the TLS longitudinal feedback system. Table 1 presents parameters related to the longitudinal feedback system. Figure 1 presents a block diagram of a longitudinal bunch-by-bunch feedback system. The system consists of a beam position monitor (BPM), a bunch phase detector, a

feedback processor, an SSB or QPSK modulator for a longitudinal feedback system, power amplifiers and kickers. The beam signals picked up by the BPM are processed by a phase detector into a baseband signal and fed to the digital feedback processor, at which the phase oscillation signal of each bunch is converted into digital form and filtered by the FIR filters. The kicker is driven by the filtered error signal to dampen the bunch motion.

The BPM sum signals are fed to the I-tech's RF front-end detector [5] and 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 and delayed to align four consecutive bunches signal into four parallel signals at a data rate of 125 MHz. These signals are fed into feedback processor. The data of every four turns is used for the input of the 50-tap FIR filters and effective number of taps is 200-tap without decimation. The measured response of the prototype FIR filter shown in Fig. 2. The corrected output is sent to the SSB modulator: the lower sideband was sent to the beam excitation amplifier and the kicker. The filter is used in current configuration, as a typical band pass filter. Sophisticated filters will be applied later.
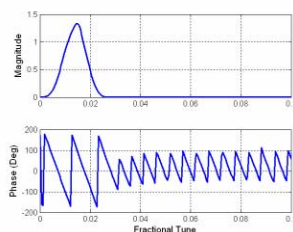

Figure 2. Measured response of the prototype FIR filter

In the four-ADC mode, the feedback processor is operated in four parallel channels of the ADC and the FIR filter. The 12-bit resolution ADC can fulfil the dynamic range requirement for a longitudinal feedback system. The bunch rate or the RF acceleration frequency is 499.654 MHz and the harmonic number is 200. The feedback processor and ADCs are operated with a clock frequency of $f_{RF}/4$. The f_{RF} was selected as the carrier frequency of the signal from the beam position monitoring electrodes. A maximum of 50 taps of the FIR filter is supported. The maximum decimation is limited to ten because of the size of the first-in-first-out memory implementation inside of FPGA. Up to 32 sets of FIR filter coefficients can be stored in the internal register of FPGA and are selectable via a USB 2.0 interface or with an external logic input. In the latter case, the switching speed is about 10 nsec. This function makes the system very flexible for use in grow-damp experiments. Up to historic 128 Mega-samples of ADC are stored in the DDR memory in the feedback processor, up to 256 ms of data can be stored in the memory. The latency time of the feedback processor is around 300 nsec. Two turns delay is used for the longitudinal feedback loop. The frequency of multiplier supplies a DAC clock at the RF frequency with a cycle-to-cycle jitter of 50ps from the ADC clock. The DAC clock can be replaced with the external clock when

the jitter is a problem. The processor is equipped with five DACs - four for the multiplexed FIR filter output and one for multiplexed raw ADC data for diagnostics and tuning. Each DAC has complementary outputs. The delay and polarity of the individual kicker must be tuned when several kicker electrodes are used for feedback. Such tuning is easily performed using these functions and outputs. A compact Flash (CF) card is used as a booting device and stores configuration data of the feedback processor. The USB2.0 interface is provided to control the processor, simplify the system and transfer the captured data. A device driver of the feedback processor for the Linux kernel 2.4 is developed and most functions are controllable. The device driver for Linux is available. The control software is installed in a Linux PC with Matlab to provide a convenient environment for the interface of the feedback processor. Matlab scripts control the accelerator through the existing Matlab interface, the feedback processor via the USB 2.0 interface and the electronic instruments via the IEEE-488 interface. This environment effectively supports various investigations.

LONGITUDINAL KICKER

A new longitudinal kicker was installed in the TLS storage ring in January 2006 to replace the old one, which suffered from low shunt impedance. The beam pipe of the kicker cavity fits the cross section of the TLS vacuum chamber, eliminating the need for tapers and also minimizing broad band impedance effects. Nose cones are employed to maximize the shunt impedance of the structure.

Longitudinal coupling impedance was measured in house by the coaxial wire method with resistive matching networks at input and output ports. The measured peak coupling impedance of the accelerating mode is 684 Ω with an FWHM bandwidth of 280 MHz. It corresponds to a shunt impedance of 1368 Ω at the centre frequency. These results agree very well with those calculated by GdfidL, as shown in Fig. 3.
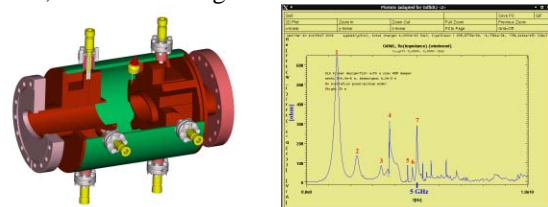

Figure 3. Longitudinal kicker and GdfidL modelling results.

COMMISSIONING RESULTS

Figure 4 shows the typical filling patterns of a user run of TLS and the bunch oscillation signal with the feedback loop open and closed. The 16 ns period in the filling pattern is associated with the injection scenario. The bunch oscillation signal is large when the feedback loop is opened. After longitudinal instability is suppressed, the bunch oscillation is clear. Figure 5 shows the beam spectrum. The major longitudinal mode near 740 MHz was suppressed by the feedback loop. A grow/damp

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experiment was also performed. Figure 6 shows the evolution of the envelopes and modes at 300 mA. The mode spectrum shown is dominated by only two modes. Figure 7 shows the temporal dynamic of the grow/damp experiment. Figure 8 shows the effect of the feedback loop on the synchrotron radiation profile. Since the synchrotron radiation monitor is located in the dispersion region, the energy oscillation contributed considerably to the beam size. After the feedback loop was turned on, the horizontal beam size decreased drastically. Figure 9 presents the streak camera image without and with feedback. A large oscillation was observed without feedback. The energy oscillation almost disappeared when the feedback loop was closed.
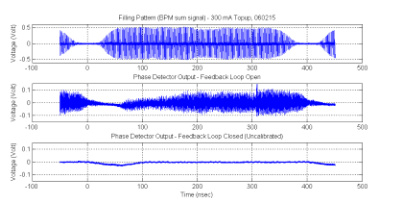
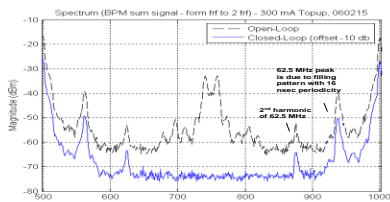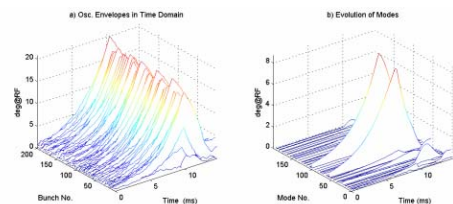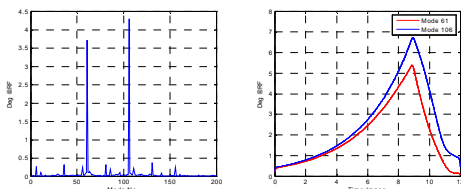Figure 4. Filling pattern and bunch oscillation signal with and without feedback loop.

Figure 5. Beam spectrum with and without longitudinal feedback loop.

(a) Evolution of oscillation envelope.   (b) Evolution of modes.

Figure 6. Evolution of bunch oscillation envelope and modes.

(a) Modal spectrum. (b) Grow/damp response.

Figure 7. Modal spectrum and temporal behaviour of the unstable modes. Only two modes are dominated the instability.

SUMMARY

This report summarizes the results of commissioning the new longitudinal feedback system. The feedback system is presently in service. The feedback system suppresses the residual energy oscillation, increasing the brightness of the machine. The performance, reliability and functionality of the system are currently being improved.
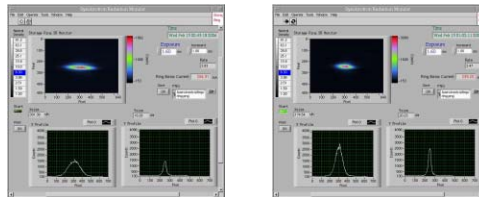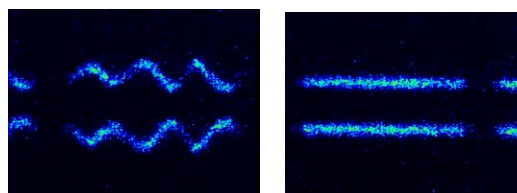

Figure 8. Transverse beam profile with and without longitudinal feedback. Source point of the synchrotron radiation is in the dispersion region ($\eta \approx 0.108$ m). The left figure is turned off feedback. Longitudinal feedback loop is effectively to reduce the horizontal beam size, is shown in the right figure.

(a) Open loop   (b) Closed loop

Figure 9. 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 effectively suppresses the longitudinal motion.

ACKNOWLEDGEMENT

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