PRELIMINARY STUDY OF A BUNCH-BY-BUNCH MONITORING SYSTEM FOR THE TPS BOOSTER SYNCHROTRON

Y. S. Cheng*, K. T. Hsu, P. C. Chiu, C. Y. Wu, J. C. Huang
National Synchrotron Radiation Research Center, Hsinchu, Taiwan

Abstract

The Taiwan Photon Source (TPS) booster synchrotron has been in routine operation since 2015, accelerating electron beams from 150 MeV to 3 GeV at a 3 Hz repetition rate. Ensuring beam stability during the energy ramp is essential, particularly through tune correction to mitigate particle loss associated with betatron resonances. Tune variations primarily arise from magnetic field imperfections, space-charge effects, and injection-related errors. Effective tune control is therefore required to maintain the beam on its intended trajectory and to achieve high acceleration efficiency. To support this objective, a bunch-by-bunch feedback processor has been adapted as a diagnostic toolkit capable of measuring and tracking the booster tune throughout the energy ramp, enabling real-time correction. The system acquires waveform data using configurable multi-bunch or single-bunch triggers, and advanced signal-processing techniques are applied to suppress background noise for improved spectral clarity. Ultimately, the developed system aims to perform tune compensation to reduce tune fluctuations and enhance injection efficiency. This report summarizes the development and performance evaluation of the proposed efforts.

INTRODUCTION

The TPS booster synchrotron accelerates electron beams from 150 MeV to 3 GeV with a repetition rate of 3 Hz. The beam is injected at 150 MeV and ramped up to 3 GeV within 155 msec before extraction [1]. During this rapid acceleration process, beam losses are strongly influenced by orbit distortion, beam instability, and tune evolution.

To further investigate booster performance, a spare bunch-by-bunch feedback processor was installed in the booster for detailed studies. Uncontrolled tune shifts can lead to resonance crossing, resulting in beam loss and reduced injection efficiency into the storage ring.

The primary sources of tune variation include magnet tracking errors, residual field nonlinearities, space-charge effects at low energy, and injection mismatches. Although global tune correction schemes have been implemented, real-time and high-resolution diagnostics remain essential for fully characterizing beam dynamics during ramping process.

In this study, a bunch-by-bunch feedback processor (iGp12) is used in the TPS storage ring for bunch-by-bunch feedback [2]. A spare unit has recently been installed in the booster synchrotron for various diagnostic tests. The system enables turn-by-turn and bunch-resolved measurements of beam motion, providing additional insights into both longitudinal and transverse beam dynamics. The goal is to establish a reliable measurement framework for a better understanding of ramping behavior and to explore the possibility of further performance improvements.

SYSTEM SETUP FOR IGP12

The iGp12 system is based on a digital bunch-by-bunch feedback architecture with high-speed ADCs and FPGA-based signal processing [3]. It was deployed for the TPS storage ring to suppress beam instability since 2015. In the booster application, the initial step is used for diagnostic purposes without feedback functionality, and the system operates in acquisition mode. The booster synchrotron operates in multi-bunch and single-bunch modes. The bunch train length is selectable from several tens to several hundred bunches. The iGp12 can capture multi-bunch beam signals for all 828 buckets (harmonic number of the booster synchrotron) on a turn-by-turn basis with approximately 25 msec. Longer recording durations are achievable using decimation; down-sampling by a factor of seven is applied to record the full ramping process. Single-bunch acquisition supports a recording time of up to 160 msec.

The beam signal is obtained from BPM pickups and processed through an analog front-end to adjust phase and attenuation, thereby determining whether the detector operates in quasi-position or quasi-phase mode. Since the booster synchrotron low-level RF system includes amplitude and phase loops, the synchronous phase decreases as energy increases to ensure sufficient acceleration. Consequently, the detector cannot operate in pure position or pure phase mode throughout the entire ramp cycle. The digitized signals are synchronized with the RF frequency and revolution clock to ensure accurate bunch indexing.

The low-level RF system of the booster synchrotron regulates amplitude according to a predefined amplitude program to optimize RF acceptance. The phase is not actively controlled; however, the synchronous phase decreases by approximately 35 degrees during the ramp from 150 MeV to 3 GeV to compensate for synchrotron radiation losses, with most of the phase shift occurring near 2 GeV. This 35 degrees phase shift causes the demodulated signal to contain mixed amplitude and phase components with crosstalk; therefore, a quasi-phase representation is used to describe position and phase information. Nevertheless, this approach remains acceptable for test purposes.

Two kinds of iGp12 data memory are available to record all bunch beam data (up to 828 bunch locations) for 25 msec (~15,000 turns) and single-bunch data for 160 msec. It can be decimated from the all bunch data according to requirements to extend the recording time. To record data for the

* cheng.ys@nsrrc.org.tw

full ramping cycle, it is necessary to set a decimation factor of 7 for 153 msec duration. However, post-data processing should consider this decimation. It can capture all bunches over multiple turns. To study the detailed behavior of all bunches, the delay of the recording memory can be adjusted to observe a 25 msec segment during ramping, or to isolate a specific bunch using programmable triggering, allowing detailed investigation of localized effects. Another single-bunch memory can record any bunch over the entire ramping cycle recording time, so-called in the single-bunch mode. The concept of the data memory is shown in Fig. 1.

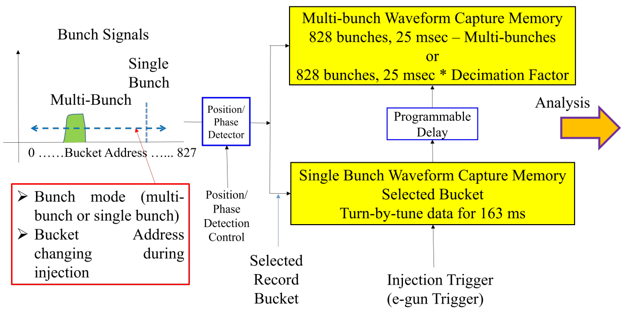
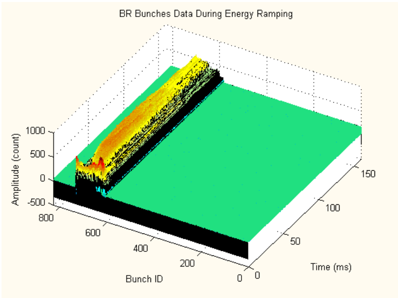
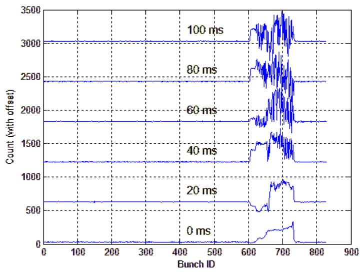


Figure 1: iGp12 based data acquisition.

The iGp12 ADC samples at the RF frequency, enabling turn-by-turn resolution. The recorded data are available for offline analysis. A typical dataset corresponds to a multi-bunch operation cycle of the booster, as shown in Fig. 2, with a bunch train of approximately 100 bunches to support multi-bunch injection. Figure 3 shows three available data formats: multi-bunch data with decimation, multi-bunch data without decimation, and single-bunch data covering the full ramping cycle for a selected bunch ID.



(a) Envelope of all bunches.



(b) Slice at different time.

Figure 2: Envelope of one of a multi-bunch injection cycle (~100 bunches) data with decimation from 150 MeV (0 ms) to 3 GeV (153 ms).

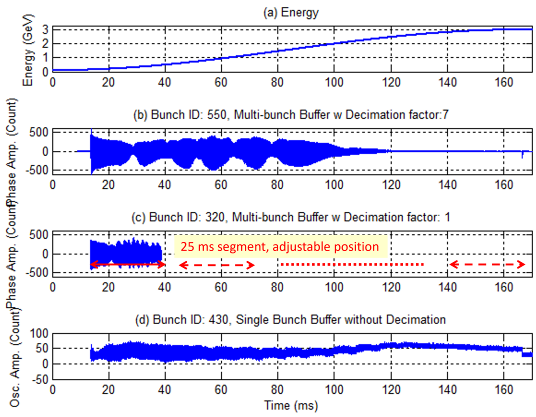


Figure 3: (a) energy ramping as function of time; (b) available data format: multi-bunch buffer with decimation (D=7); (c) multi-bunch buffer w/o decimation; (d) single-bunch buffer. In this figures, (b) and (c) data were taken in the quasi-phase detection, (d) is quasi-position detection.

OBSERVATIONS

Preliminary tests were performed to explore system limitations and potential applications for further development. For comparison, the booster tune evolution measured by the existing tune monitor is shown in Fig. 4. The observed features indicate that the vertical tune (fy) varies slightly during the ramping cycle, while the horizontal tune (fx) exhibits larger variations. This imbalance may require further optimization of the ramping waveform to improve booster performance. Additionally, ripple structures are observed in the tune spectrum, possibly due to non-ideal ramping waveforms and line-frequency interference. Further investigation is required.

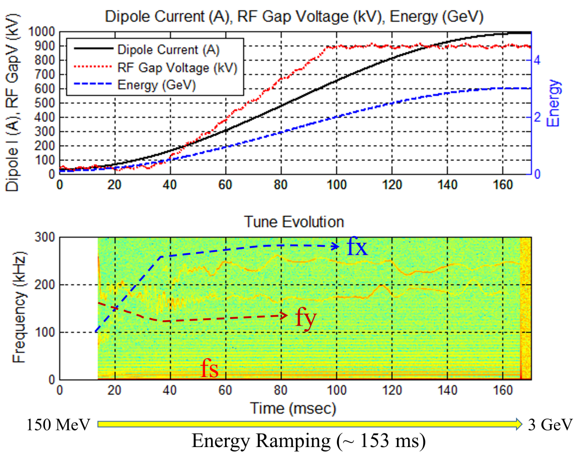


Figure 4: Booster tune monitor data based on Fourier analysis of turn-by-turn data of BPM with beam excitation for reference. The fx and fy cross around at 15 msec after beam injection of current operating condition.

The data captured for multi-bunch (~100 bunches) during the ramping process were studied using quasi-position detection mode. The information extracted from the iGp12 system is shown in Fig. 5. Data acquisition begins at beam injection. Strong energy oscillations are observed compared to weak transverse beam position signals, even though the detector operates in quasi-position detection mode. This is expected because there is no damping at the low-energy stage. The transverse oscillation amplitude is relatively small. The dominant oscillation mode appears at lower frequency (most likely resistive in nature). However, the transverse oscillations disappear (or become very weak) after approximately 15 msec of beam injection. The oscillation modes during the first 10–20 msec, particularly the transverse oscillation, are shown in Fig. 6.

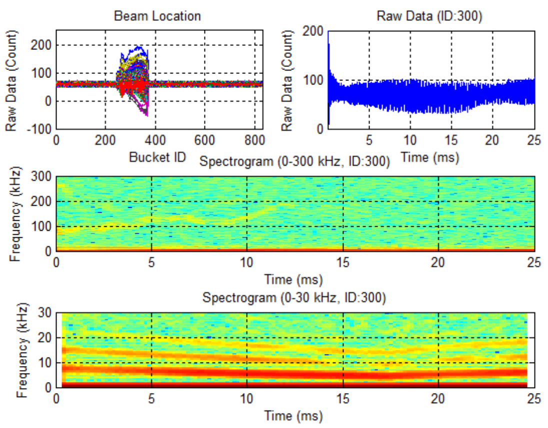


Figure 5: Typical data captured by multi-bunch buffer without decimation for the first 25 msed beam. Transverse oscillation is still observable for the first 15 msec, while very strong energy oscillation caused several harmonics clearly observable.

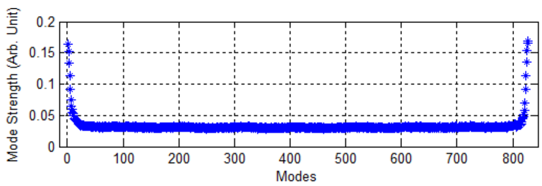


Figure 6: Relative mode strength of horizontal oscillation, lower order modes dominated.

Single-bunch data in Fig. 7 clearly show synchrotron oscillations, especially at low energy where damping is minimal. The synchrotron frequency evolves during the ramp due to changes in RF voltage and beam energy. Spectrogram analysis reveals strong synchrotron sidebands and harmonics, along with visible horizontal betatron oscillations even without external excitation.

SUMMARY

The implementation of the iGp12 system as a diagnostic tool demonstrates its capability for beam dynamics measurements in the TPS booster. The system captures beam behavior during energy ramping, including oscillation modes and tune evolution. It enables real-time observation of tune evolution, bunch-resolved analysis of longitudinal and transverse motion, and identification of beam loss mechanisms. By combining this system with BPM measurements, correlations with contributing factors can be analyzed in detail.

Further improvements are required to reduce position–phase coupling in the detector caused by synchronous phase shifts during ramping, thereby enhancing position and phase measurement accuracy. Integration of real-time tune tracking is also feasible with small beam excitation. Extension of the system to support instability diagnostics and mitigation [4–6] is under investigation. Ultimately, the developed system provides a tool for improving booster performance and achieving higher injection efficiency into the storage ring. Preliminary results demonstrate the feasibility of real-time diagnostics and the potential for future feedback applications.

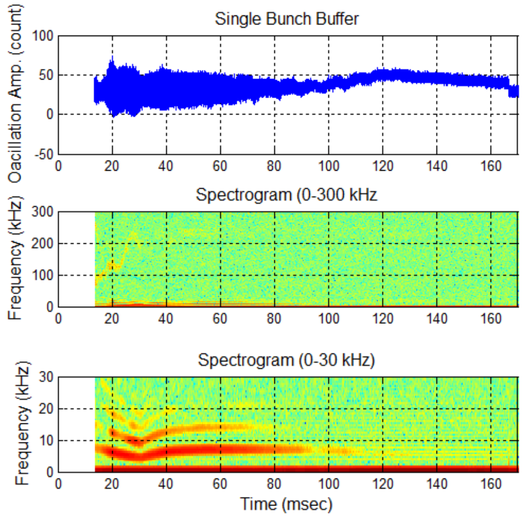


Figure 7: Strong synchrotron sideband and its harmonics observed. Horizontal betatron oscillation are observable without excitation.

REFERENCES

[1] H.-J. Tsai *et al.*, "First Year Performance of the TPS Booster Ring", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 634–636. doi:10.18429/JACoW-IPAC2016-MOPOR017

[2] Y.-S. Cheng, K. T. Hsu, K. H. Hu, C. H. Huang, and C. Y. Liao, "Commissioning of the Bunch-by-Bunch Transverse Feedback System for the TPS Storage Ring", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 612–615. doi:10.18429/JACoW-IBIC2016-WEPG02

[3] iGp12, https://www.dimtel.com/products/igp12

[4] T. Atkinson *et al.*, "Status and Prospects of the BESSY II Injector System", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2826–2828. doi:10.18429/JACoW-IPAC2016-WEPOW007

[5] T. Atkinson *et al.*, "Studies of Longitudinal Instabilities in BESSY II Booster", HZB/Dimtel, 2017. https://wiki.dimtel.com/lib/exe/fetch.php?media=dim:bessy_booster_28may17.pdf

[6] M. McAteer, "Bunch-by-bunch feedback in the BessyII Booster", presented at the I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics, Germany, Mar. 2024. https://indico.kit.edu/event/3742/contributions/15189/attachments/7286/11590/20240304_BII_booster_bbfb_McAteer.pptx