

IMPLEMENTATION AND PERFORMANCE EVALUATION OF A HIGH-RESOLUTION BUNCH-BY-BUNCH PHASE DETECTION SYSTEM WITH GEOMETRIC CALIBRATION

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Abstract

A high-resolution, real-time bunch-by-bunch phase detection system has been developed and deployed at the Taiwan Photon Source (TPS) to monitor and analyze synchronous phase behavior. The system is integrated with the control system to implement the remote phase adjustment function. The detector architecture utilizes an analog I/Q demodulation scheme operating at the 1.5 GHz third harmonic of the RF frequency to achieve precise phase extraction. Limited by hardware non-idealities, DC offsets and quadrature phase imbalances distort the I/Q signal trajectory into an elliptical profile, leading to periodic measurement errors. To address these issues, a digital calibration strategy based on ellipse-fitting is implemented to eliminate offsets and quadrature errors within the I/Q channels. After calibration, the phase error of this system at 1.5 GHz is within 1.5° , therefore, when used to measure a 500 MHz signal, the corresponding phase error is within $\pm 0.5^\circ$. The extracted phase data is integrated into the accelerator control system with a 3 Hz update rate, enabling real-time visualization of transient beam loading effects. Furthermore, the system's capability to record 700 turns of bunch motion for phase variation analysis,

INTRODUCTION

The Taiwan Photon Source (TPS) is a 3 GeV synchrotron light source located at the National Synchrotron Radiation Research Center (NSRRC), requiring exceptional beam stability to support high-brightness research applications. To improve beam lifetime by increasing the bunch length, a 1.5 GHz superconducting harmonic cavity (HC) has been installed. However, due to the transient beam loading effects, this configuration introduces significant synchronous phase shifts along the bunch train [1, 2]. As a result, a bunch-by-bunch (BbB) phase detection system is required to monitor these effects and allow a variety of applications during daily operations.

A common method for measuring the BbB phase is using high-sampling-rate oscilloscopes or analog-to-digital converters (ADCs) [3–5] to capture raw waveforms, followed by zero-crossing detection to extract phase information. However, this method requires powerful computing capabilities. Another technique utilizes gated circuits to detect the phase of specific bunches, often integrated into turn-by-turn beam position monitor (BPM) systems [6, 7]. Additionally, streak cameras can provide exceptional phase resolution, but they

are typically constrained by high equipment costs and lower data refresh rates [8].

To fulfill the requirements for real-time monitoring within the control system, a detection scheme employing an analog in-phase and quadrature (I/Q) demodulator is proposed. In this approach, the sampling rate is synchronized with the RF clock, allowing phase calculation via simple trigonometric functions. This effectively reduces the computational resources required for the real-time monitoring of long bunch trains.

This paper describes the implementation of the TPS bunch-by-bunch phase detection system, including its hardware component layout and control software development. To overcome hardware non-idealities, a geometric calibration approach based on an ellipse-fitting algorithm is used to digitally compensate for signal distortions. Finally, the system was utilized to detect beam phase shifts and variations during routine storage ring operations.

SYSTEM ARCHITECTURE

The essential method for extracting the bunch-by-bunch (BbB) phase relative to the accelerator's master clock is analog I/Q demodulation. The architecture of the system is shown in Fig. 1. The system synchronizes with the TPS master RF clock at about 500 MHz, which serves as the input reference for a phase-locked loop (PLL) synthesizer with an integrated voltage-controlled oscillator (ADF4372), generating a 1.5 GHz third-harmonic signal. This reference signal is divided into two local oscillator (LO) paths, where a 90° quadrature phase shift is achieved by adjusting the physical path lengths. Phase trimmers are integrated into both paths for precise calibration of the effective electrical length.

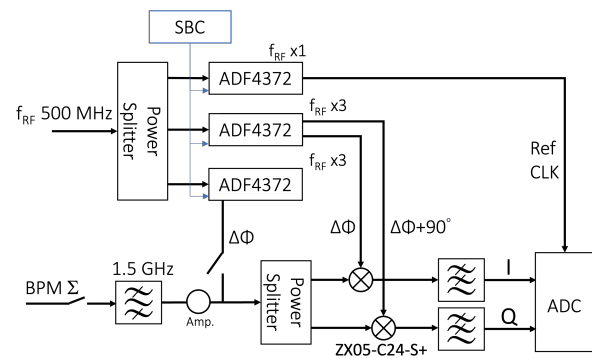


Figure 1: The infrastructure of the bunch-by-bunch phase detector.

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The BPM electrode signals are processed through a 1.5 GHz comb filter, amplified by 15 dB, and split into two channels for I/Q demodulation. By utilizing the 1.5 GHz harmonic, the system achieves a 120° detection range while enhancing measurement resolution through frequency multiplication. The resulting I/Q components are digitized by a Libera Digit 500 system after low-pass filtering. To ensure synchronous bunch-by-bunch sampling, the ADC clock is phase-locked to an external reference, with its phase delay optimized to capture peak bunch amplitudes for maximum SNR. The system's control layer employs a Raspberry Pi to manage the frequency synthesizer via SPI. Both the digitizer and synthesizer are integrated into the accelerator infrastructure using the EPICS framework. A Python-based engine processes bunch phases in real-time, publishing the results as EPICS Process Variables (PVs) with a 3 Hz refresh rate. The platform supports both real-time monitoring of 700-turn bunch dynamics and high-speed data acquisition for offline diagnostics.

GEOMETRIC CALIBRATION STRATEGY

While analog I/Q demodulation technology offers excellent sensitivity and minimal data latency, its measurement precision is significantly constrained by hardware limitations, such as component manufacture tolerances and cable length mismatches. These hardware non-idealities distort the ideal circular I/Q trajectory into an off-center ellipse.

One of the error sources is the DC offset from the mixers (ZX05-C24-S+), which is caused by residual voltages within the components and LO leakage from the reference clock path, displacing the trajectory from the coordinate origin and introducing periodic non-linear phase distortions [9–11].

Gain imbalances from mismatched amplification and transmission losses result in amplitude asymmetry, while quadrature phase errors—arising from cable mismatches or component tolerances—tilt the elliptical path, further compromising phase accuracy.

To calibrate these errors, this study utilizes a geometric ellipse-fitting calibration. Test signals simulating BPM outputs are generated by a synchronized frequency synthesizer. By sweeping the output phase from 0° to 360°, enabling acquisition of the corresponding I/Q measurement signals. During the scanning procedure, the ADC captures the corresponding raw in-phase and quadrature components, I_{raw} and Q_{raw} , which form the elliptical trajectory designated for calibration. The captured I/Q samples are subsequently modeled for parameter extraction using the following implicit quadratic equation:

$$I_{raw}^2 + aQ_{raw}^2 + bI_{raw}Q_{raw} + cI_{raw} + dQ_{raw} + e = 0.$$

By solving the linear system formed by the captured samples, the coefficients a , b , c , d , e are extracted to quantify the hardware-induced distortions. These coefficients are translated into specific physical parameters: the linear terms (c , d) define the DC offsets, the cross-product term (b) determines

the quadrature phase error (ψ), and the quadratic term (a) characterizes the gain ratio.

To minimize signal distortion at the source, these parameters are applied as real-time compensations. The calculated DC offsets are applied to the ADC input to re-center the signal trajectory at the origin. Simultaneously, the gain ratio is used to balance the I and Q channel amplitudes, rectifying trajectory deformation. For the phase error, the extracted ψ value provides the basis for physical path calibration, where cable lengths are adjusted to achieve a 90° quadrature relationship between the two channels. These integrated adjustments revert the elliptical trajectory into a near-ideal circle.

PERFORMANCE EVALUATION

To calibrate the phase detector, the corresponding I and Q values were recorded across various generated phase shifts, as shown in Fig. 2.

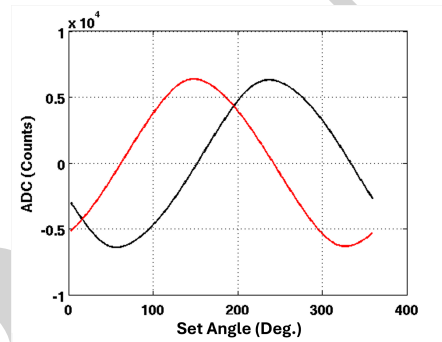


Figure 2: Measured I and Q components prior to calibration, showing significant negative DC offsets in both channels.

In the initial state, the calculated I and Q offsets were -470 and -562 (in ADC units), respectively, while the gain imbalance was 1.02 and the quadrature phase error was 2°. As shown in Fig. 3, the resulting I/Q Lissajous trajectory deviated noticeably from the ideal circular path, leading to a phase error exceeding $\pm 8^\circ$.

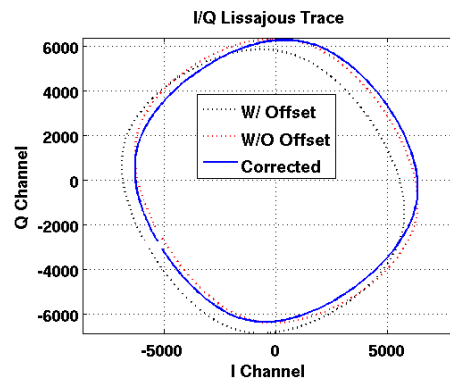


Figure 3: The measured I/Q trajectory (black) and the calculated calibrated circular I-Q trajectory (blue); due to system nonlinearity, residual square distortion still exists.

The calibrated parameters for DC offsets and gain ratios were then applied to calibrate the ADC module, and the

cable lengths were adjusted to restore the 90° quadrature relationship. The trajectory approximates a standard circle, and the phase error decreases to approximately $\pm 2^\circ$, as illustrated in Fig. 4.

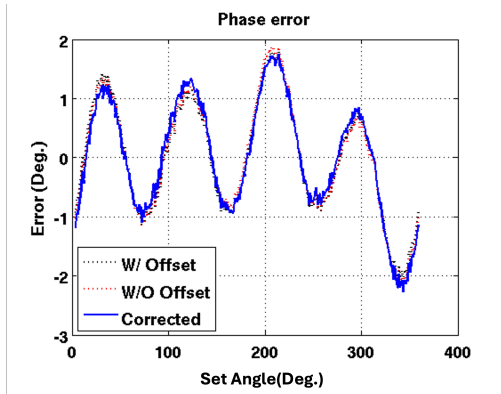


Figure 4: After hardware calibration, the measured phase error was reduced to approximately $\pm 2^\circ$.

After several calibration iterations, the final I/Q offsets were reduced to 3.51 and -9.52 , respectively, while the gain imbalance improved to 1.006. The quadrature phase error was reduced to approximately 0° . The residual phase error is within $\pm 1.5^\circ$ at 1.5 GHz. Since phase deviation caused by timing offsets is linearly proportional to frequency, this result corresponds to an equivalent phase error of $\pm 0.5^\circ$ at 500 MHz.

BEAM MEASUREMENT

The detector was deployed to monitor the synchronous phase drift of the bunch-by-Bunch system at TPS. Figure 5 illustrates the filling pattern and synchronous phase shift for a 500 mA storage current. The phase shift is about 30° when the HC is active, which is a direct consequence of the longitudinal potential well flattening used to improve beam lifetime.

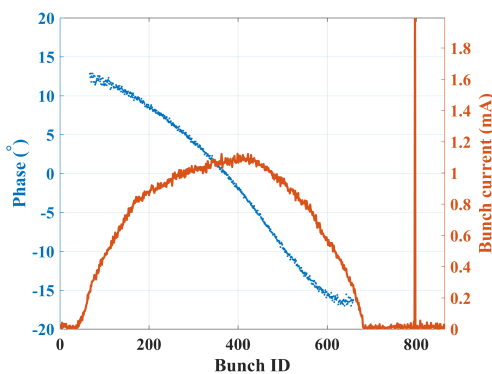


Figure 5: The filling pattern and synchronous phase shift with a stored beam of 500 mA.

Figure 6 shows the graphical user interface (GUI) of the bunch-by-bunch phase detection system, which provides a global view of the phase, amplitude, and stability (STD) across all 864 bunches. Furthermore, the system enables

tracking of individual bunches; for instance, the phase variation of the 200th bunch can be monitored over 700 consecutive turns. The GUI update corresponds to the analysis of 700 turns (about 604,800 bunches), with an update rate of 3 Hz. Additionally, the system also supports high-speed data acquisition for offline analysis.

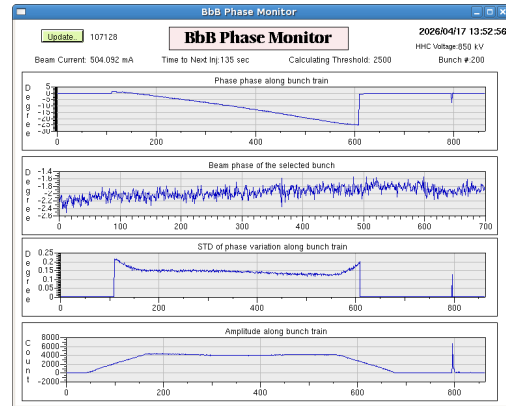


Figure 6: The graphic user interface of the bunch-by-bunch detect.

CONCLUSION

This paper presents a high-precision bunch-by-bunch phase detector utilizing an I/Q demodulation scheme at the 1.5 GHz third harmonic. To overcome hardware non-idealities, a geometric ellipse-fitting calibration was implemented, effectively compensating for DC offsets and quadrature phase errors. Following calibration, the system achieves a residual phase error of less than $\pm 0.5^\circ$ across a 120° operating range. The system has been successfully integrated into the TPS control system, the detector provides real-time monitoring of all 864 bunches over 700 turns at a 3 Hz refresh rate. This development offers a reliable diagnostic tool for analyzing longitudinal beam dynamics and transient beam loading effects under daily operation.

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