BUNCH BY BUNCH POSITION MEASUREMENT AND ANALYSIS AT PLS-II

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Abstract

Stable electron beam position and constant beam current to realize a constant photon flux is crucial in storage ring. Therefore, diagnostics for bunch by bunch motion important. We developed the bunch by bunch measurement system at PLS-II. The system consists of 4 channel button pick-up, 20 GHz oscilloscope, 800 MHz low pass digital filter, and SVD analysis. The system is used to diagnose injection oscillation due to kicker error and instability occurred in operation.

INTRODUCTION

After the completion of the PLS-II project to upgrade PLS on March 21, 2012, Pohang Light Source II (PLS-II) [1] is now in full operation. As a result of the upgrade, the PLS beam energy increased from 2.5 GeV to 3.0 GeV, and the stored beam current increased from 200 mA to 400 mA. The emittance is improved from 18.9 nm at 2.5 GeV to 5.8 nm at 3 GeV while the PLS storage ring (SR) tunnel structure remains unchanged. In addition, the top-up mode operation is used to stabilize the stored electron beam orbit and the synchrotron radiation flux. Currently, we provides the stable photon flux 97 % of the user beam time. Issues about the beam stability are the injection orbit transients and the occasional beam loss.

During the top-up operation, the beam injection excites an oscillation of the stored beam. The excited oscillation effectively enlarges the stored beam emittance and modulates the photon beam intensity. For example, 1~8 % systematic dips in the photon beam flux pattern of each beam line occurs during the top-up injection in PLS-II. Furthermore, future of storage ring-based light sources will go toward an ultra-low emittance. In these light sources, a lifetime of stored electron beam will be extremely short and beam injection will be fulfilled more often in top-up operation. Therefore, for achieving the high performance of a top-up operation for user experiments in the future low emittance ring, it will be crucial to suppress the stored beam oscillation during top-up injection. Partial or entire beam loss occurs time to time at PLS-II. Through the fill pattern measurements, we identified the coupled bunch instability is one of the reason.

Beam dynamic phenomena described by bunch-by-bunch motion are important issues for a storage ring and are described by various theoretical formalisms. Direct measurements of the beam position related to different dynamical mechanisms are a useful information to accelerator optimization. In PLS-II, 20 GHz sampling oscilloscope synchronized with injection event (or triggered by beam loss signal) is used to measure direct bunch by bunch motion. Based on the measured data, the principal component analysis had been performed to get the insight into beam dynamic phenomena such as couple bunch instability and beam oscillation due to kicker leakage.

In this paper we describe the bunch by bunch (BbB) position measurement system in PLS-II. Section 2 presents the system layout and the data processing for the BbB BPM. Section 3 describes the analysis of the injection transient using BbB BPM. Analysis of the instabilities are described in Section 4. Section 5 presents our conclusions.

SYSTEM LAYOUT AND DATA PROCESSING

Figure 1 shows overall layout of the BbB measurement system. The system consist of signal pick-up, 750 MHz Low Pass Filter (LPF) and 20 GHz sampling oscilloscope. The pick-up is located at cell 12 in the PLS-II storage ring. A typical PLS-II BPM [1] is used as the pick-up part of the bunch by bunch measurement system. The BPM consists of an octagon vacuum chamber and four pick up electrodes for signal pick-up. The vacuum chamber has a horizontal aperture of 66 mm and a vertical aperture of 22 mm. The horizontal separation between two pick-up electrodes, which is mainly defined by sensitivity, is 15 mm. The pick-up electrode for the BbB BPM consists of a central conductor with a button electrode, an outer conductor with a SMA type feedthrough, and a ceramic insulator. Simulated output signal in the time domain is shown in Fig. 2(a). As shown in the figure, the generated output signal is completely damped within 0.5 ns. Note that the time gap between bunches is around 2 ns and harmonic number is 470.

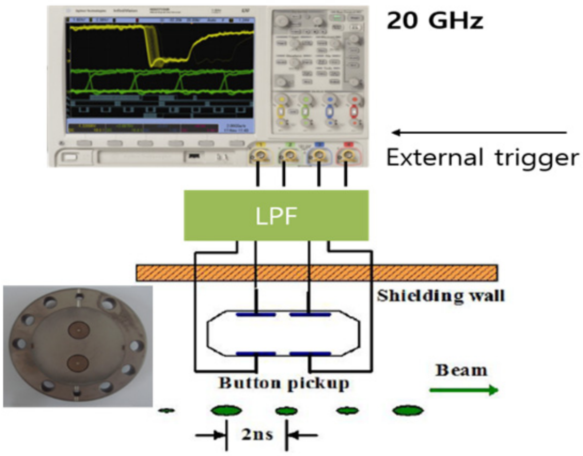

Figure 1: The layout of the bunch by bunch BPM system.

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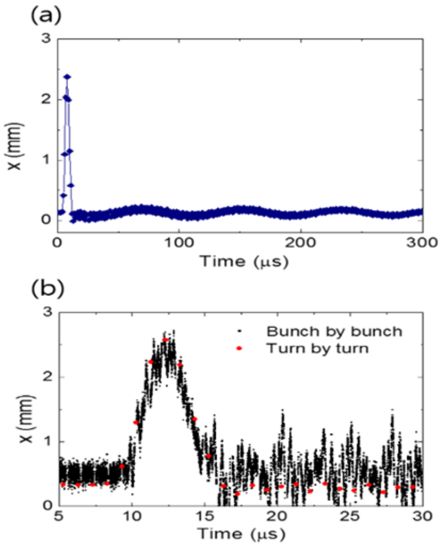

Figure 2: Injection transient analysis using turn by turn (TbT) BPM and bunch by bunch (BbB) BPM. (a) TbT BPM analysis. (b) Comparison between TbT and BbB.

DIAGNOSIS ON INJECTION TRANSIENT

In top-up mode operation, a small amount of the beam current is injected into the stored beam to keep the stored beam current almost constant. During the top-up injection, four kicker system changes the position of a stored bunch to meet the injected one, and then changes it back to the original orbit with the injected bunch. Unfortunately, an oscillation in stored beam can cause a perturbation in the beamline experiments because of the tilts of the bump magnets, the leakage field from septum magnet and the differences among the magnetic fields of the four kicker magnets. Figure 2(a) shows a horizontal turn by turn oscillation of the stored beam during the 300 μs after the kicker magnet on. A bumped orbit is shown at first 7 μs and one can see residual beam oscillation. The oscillation of the stored beam has an effect on the photon position and flux stability in beamline experiments. Therefore, the source on stored beam oscillation must be investigated and suppressed.

We gathered BbB position data to analyse the injection transient motion. Figure 2 (b) shows the comparison between the TbT position data and the BbB position measurement of the horizontal motion during the 20 μs after the kicker magnet on. The BbB position data shows the excitation of the residual bunch by bunch oscillation after the injection more clearly. Kicker field shape systematic error caused by field asymmetry of kicker is also shown in the figure.

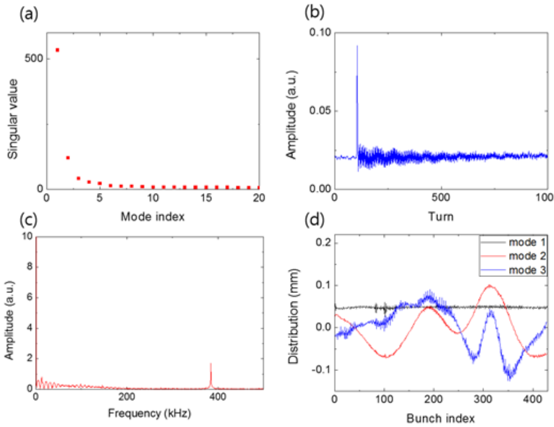

Figure 3: SVD analysis of the horizontal injection transient. (a) Singular values. (b) The amplitude of the first principal mode. (c) FFT of the oscillation amplitude. (d) Distributions of the principal modes.

In order to explore the physical meaning in the measured bunch by bunch position data, singular-value decomposition (SVD) analysis was applied. In general, the singular-value decomposition of the data matrix containing beam position yields a spatial-temporal mode analysis of beam motion by effectively accomplishing statistical principal component analysis. Mathematically, the SVD of a matrix B yields [2]

$$B = USV^T = \sum_{i=1}^{d} \sigma_i u_i v_i^T , \qquad (1)$$

where and U, V are orthogonal matrices, S is a diagonal matrix with nonnegative σ along the diagonal in decreasing order, is the number of nonzero singular values, and the vector u and v are the left and right singular vector, respectively. Each set of {u, v} defines a spatial-temporal mode, where u gives the temporal variation, v gives the spatial variation. The singular values reveal the system dimensionality and relative magnitudes, while each set of singular vectors form an orthogonal basis of the various spaces of the matrix.

We performed a singular-value decomposition analysis for the bunch position matrix B. Matrix of 1,000 samples each for the 430 bunches are taken in the SVD analysis. Here 1,000 samples correspond to 1 ms time scale. The diagonal element of the singular matrix, S provides an estimate of the modes. Figure 3 (a) shows that there are floors of these singular values and a few modes are separable from the floors. The first singular value of the matrix is predominantly large. It indicates that there is a major motion of the matrix. Figure 3 (b) and (c) shows the first temporal eigenvector from matrix B and it's frequency component, respectively. The first temporal eigenvector clearly shows typical horizontal beam motion, that consist of large orbit shift during kicker on and energy oscillation and betatron oscillation after kicker off. In Fig. 3 (c), betatron tune and synchrotron tune are shown in frequency component of the first temporal eigenvector. Based on the singular values, only two major modes in Fig. 3 (d) with relatively large singular values were worth studying. The first mode is uniform along the bunch index and the second mode is showing oscillation along the bunch index. Therefore, the singular value of the first mode is considered as the amplitude of the injection bump and the betatron damping and the singular value of the second mode is considered as oscillation amplitude along bunch caused by kicker waveform error.

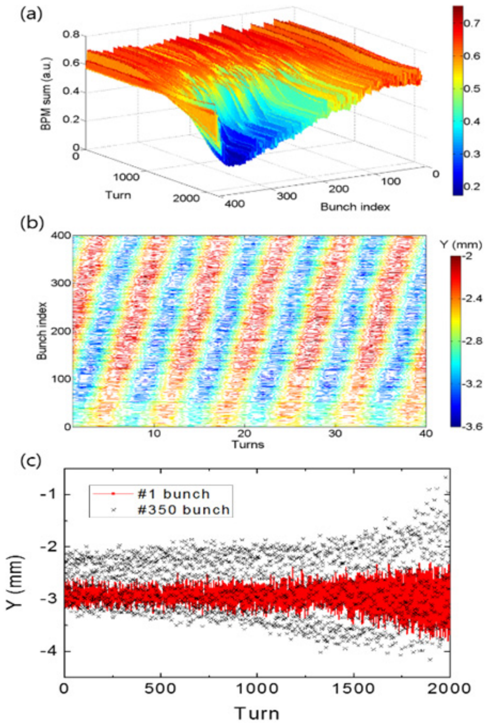

Figure 4: Bunch by bunch bpm analysis during the beam loss from the coupled bunch instability. (a) BbB BPM sum during last 2 ms before the beam loss. (b) BbB vertical oscillation before the beam loss.

DIAGNOSIS ON INSTABILITIES

A medium energy storage ring as the PLS-II with a beam energy of 3 GeV can meet high photon energies. In-vacuum undulators with a period length of 20 mm and a peak field of 0.97 T are used in the PLS-II ring to produce such X-rays in the fundamental or higher harmonics. 12 narrow gap in-vacuum undulators have been in operation. These narrow gap in-vacuum undulators will produce coupled bunch instability by resistive wall impedance and limit the stored beam current. Therefore, a bunch by bunch feedback system should be operated to suppress coupled bunch instabilities.

A feedback system for transverse betatron oscillations or longitudinal synchrotron oscillations is an effective device for suppressing beam instabilities that limit the beam current or the quality of the stored beam. Moreover, the feedback system can rapidly damp the beam oscillations excited by injection perturbations that are harmful to user experiments. The bunch by bunch feedback system detects transverse or longitudinal positions of a beam, processes the position data to calculate a kick signal, and kicks the beam to damp the oscillations. However, exploring instability phenomenon in high current operation is important to understand the machine and make standard to upgrade TFS system for better performance.

Transverse feedback system is turned off in normal operation condition (360 mA with 400 bunch). As a result, beam loss is occurred and the phenomenon of coupled bunch instability is investigated using BbB position measurement. The process of beam loss is described in Fig. 4 (a). Note that 400 bunches among total 470 rf buckets are filled and 70 rf bucket (clearing gap) are emptied. Unlike bunches in head part after clearing gap, bunches are lost in tail part. Compared with horizontal motion, vertical bunch motion have large oscillations. Figure 4 (b) shows contour map for the vertical oscillation along bunches and turns. Due to fractional vertical tune of 9.145, oscillation peak is repeated at every 7 turns. This implies strong vertical betatron oscillation. In addition to strong vertical betatron oscillation, the betatron phasing along the bunch train is obviously observed. It seems like the beam is under the influence of the 1st coupled bunch mode excited by the resistive wall impedance. Figure 4 (c) shows the beam oscillations of 1st bunch and 350th bunch along turns. Compared with 1st bunch oscillation, 350th bunch oscillation is large and causing beam loss.

General beam motion for the equation of motion with the wake function over the entire circumference can be described as

$$y_n^{\mu} \propto \exp(2\pi i \frac{\mu n}{M}) \exp(-i\Omega_{\mu} t) \qquad (2)$$

The solution describes the behaviour of a mode consisting of a particular pattern of transverse bunch positions, and oscillating with a particular frequency. The various modes are indexed using the symbol μ. The mode number μ gives the phase advance between the betatron position of one bunch and the next. The frequency of a mode is represented by Ωμ (each bunch performs oscillations with frequency Ωμ as it moves around the ring.) and the imaginary part of gives the growth rate of the corresponding mode. For the PLS-II normal operation with 360 mA beam current, growth time is estimated as 2 ms in considering 6 mm gap 10 m long in-vacuum undulator (copper plate) and 11 mm gap 270 m long aluminium pipe.

CONCLUSIONS

Turn by turn measurement of the transverse beam position in the storage rings have limit for the investigation of the injection transient, coupled bunch instabilities, and so forth. We designed and implemented the bunch by bunch transverse position measurement system at the PLS-II. The field error of the injection kicker is revealed through the bunch by bunch measurement of the injection transient. Beam loss by the resistive wall impedance was also investigated.

ACKNOWLEDGEMENT

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