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# INJECTION TRANSIENT STUDY USING 6-DIMENSIONAL BUNCH-BY-BUNCH DIAGNOSTIC SYSTEM AT SSRF *

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## *Abstract*

Beam instability often occurs in the accelerator and even causes beam loss. The beam injection transient process provides an important window for the study of beam instability. Measurement of the bunch-by-bunch dynamic parameters of the storage ring is useful for accelerator optimization. A 6-dimensional bunch-by-bunch diagnostic system has been successfully implemented at SSRF. The measurements of transverse position and size and longitudinal phase and length are all completed by the system. Button BPM is used to measure beam position, phase and length, and the synchrotron radiation light is used to beam size measurement. Signals are sampled simultaneously by a multi-channel acquisition system with the same clock and trigger. Different data processing methods are used to extract the 6-dimensional information, where delta-over-sum algorithm for beam position extraction, Gaussian fitting algorithm for beam size extraction, zero-crossing detection algorithm for beam phase extraction and the two-frequency method for bunch length extraction. The system set up and performance will be discussed in more detail in this paper. The application of the injection transient study brings a lot of interesting phenomena and results, which will be discussed as well.

## INTRODUCTION

The Shanghai synchrotron radiation facility (SSRF) is the third synchrotron radiation light source facility in Shanghai China, which can produce broad rates of X-rays for primary scientific research and applications in other domains. The SSRF consists of a 150MeV linear accelerator, a 3.5GeV booster synchrotron and a 3.5GeV storage ring. In the user operation mode, about 500 bunches are stored with 2ns spacing in the storage ring. The harmonic number is 720 with the RF frequency of 499.654MHz [1]. In order to take full advantage of the SSRF, phase-II project is under construction since 2011, 16 beam lines would be built and the electron storage ring would be upgraded. More insertion devices (IDs) with small gaps will be added, which will cause beam instability problems.

For the construction and operation of the machine, if the distribution of high energy particles in three dimensions and the evolution over time can be measured, almost all other parameters can be derived from the above measurements. Therefore, bunch-by-bunch diagnostics is necessary for the bunching beams. Once the diagnostics is realized, it can be used to online monitor the steady or unsteady beam parameters during the user operation mode, which is of great importance for the operation mode optimization and the capture of transient process. At the same time, it is also a useful tool for further analysis of instability, such as the tremendous change of betatron amplitude and beam size or phase.

In the injection system of the SSRF storage ring, there is a set of beam kickers, which is used to change the momentum of a bunch to meet the injected one [2]. Then, it can change back to the original orbit with the injected bunch. However, due to the imperfect mount, align and configure of the kickers, residual betatron oscillations occurred in the injection system. Therefore, bunches would be affected by the kicker field or the wake-fields from preceding bunches. The bunch-by-bunch diagnostics is a machine research tool for wake field and impedance study.

In recent years, Beam Instrumentation (BI) group at SSRF has also been focusing on the development of bunch-by-bunch diagnostics since 2012. If the bunching beam is assumed to be Gaussian in the three-dimensional space, six spatial parameters (($x$, $y$) in the transverse position, ($\sigma x$, $\sigma y$) in the transverse size, ($z$, $\sigma z$) in the longitudinal phase and length) can fully describe an independent bunch with the bunch charge. A 6-dimensional (6D) bunch-by-bunch diagnostic system has been set up to measure the parameters simultaneously at SSRF.

## PRINCIPLES

In the acquisition of beam signals, the synchrotron radiation (SR) light is the most ideal signal because it contains all beam information, whereas the button-type beam position monitor (BPM) cannot get the transverse size information. However, it is easy to condition and capture signal for the button BPM signal, and the SR light signal is limited by the bandwidth of the signal conditioning and data acquisition system. So, to realize the 6-dimensional diagnostic system, we use the SR light to obtain the transverse position and size information and use the button BPM to obtain the longitudinal phase and length information or transverse position as well.

### *Optical Imaging System*

Figure 1 shows the optical direct imaging system in the bunch-by-bunch size system. The concave lens (Lens 1) and convex lens (Lens 2) are used to focus and magnify the light spot, and to adopt the pixel size to the photoelectric detector. The visible light from the SSRF storage ring was separated into two paths through a reflecting mirror: one path was toward the interferometer system for spread function (PSF) calibration, and the other one was toward the bunch-by-bunch size measurement. A diaphragm was used to correct the deformation of the Be mirror. Since the Be mirror deformation mainly occurred in the vertical direction, the measurement of beam vertical size was destroyed. Therefore, we were more concerned with the measurement of beam horizontal size, and the horizontal size result was

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about 53um by the experimental calibration based on the interferometer system [3].

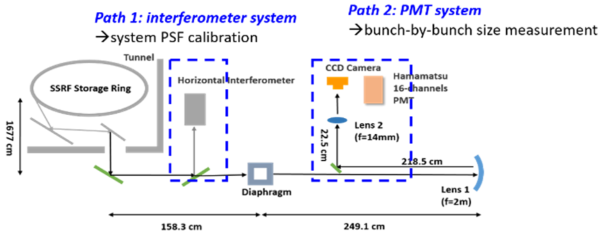

Figure 1: Optical diagram of direct imaging system.

## Button BPM

Since the BPM signal contains all beam information except the transverse size and its signal conditioning and capture is easy, we use it to measure the beam position, phase and length. Figure 2 is the cross section of a button BPM [4]. A line charge at the position (*δ*, *θ*) within the probe radius *a* and pipe radius *b*. The button voltage is produced by the current out of the button and the impedance (Z) seen by this current, which can be expressed as:

$$V_b(t) = \frac{\pi a^3 Z}{2\pi b \beta c} \cdot \frac{t-t_0}{\sigma^2} \cdot I_0(t) \cdot F(\delta,\theta)\,. \tag{1}$$

where the current equation is related to longitudinal phase (t0) and length (σ):

$$I_0(t) = \frac{eN}{\sqrt{2\pi}\sigma}\exp(-\frac{(t-t_0)^2}{2\sigma^2})\,. \tag{2}$$

and the position correlation parameters are:

$$\begin{aligned} F(\delta,\theta) &= \frac{a^2-\delta^2}{a^2+\delta^2-2a\delta\cos\theta} \\ \delta &= \sqrt{x^2-y^2} \\ \theta_{A,B,C,D} &= \frac{m\pi}{4} - \tan^{-1}(\frac{y}{x}),(m=3,1,7,5) \end{aligned}\,. \tag{3}$$

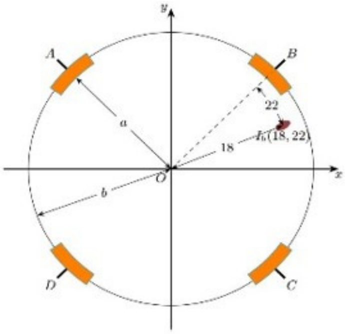

Figure 2: Cross section of button-type BPM.

## 6D Information Extraction Methods

In our experiments, we used delta-over-sum (⊿/∑) method for transverse position measurement, Gaussian fitting for transverse size measurement, zero-crossing detection method for longitudinal phase measurement and two-frequency method for longitudinal length measurement.

**Delta-over-sum Method** The main method of beam position measurement is the peak sampling of the button BPM signals and calculated by the delta-over-sum algorithm [5]. The equation is as follows:

$$\begin{aligned} x &= k_x \cdot \frac{(V_A(t)+V_D(t))-(V_B(t)+V_C(t))}{V_A(t)+V_D(t)+V_B(t)+V_C(t)} \\ y &= k_y \cdot \frac{(V_A(t)+V_B(t))-(V_C(t)+V_D(t))}{V_A(t)+V_D(t)+V_B(t)+V_C(t)} \end{aligned}\,. \tag{4}$$

Among them, the factors ($k_x$, $k_y$) require online and timely calibration. At the same time, phase drift occurs during the sampling of BPM signals.

**Gaussian Fitting Method** Assuming that the bunch is in Gaussian distribution, we can get four symmetric sampling points from the SR light signal if the channels are adjusted properly (as shown in Fig.3).

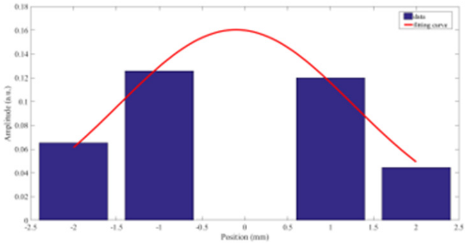

Figure 3: Four-channel sampling signal and Gaussian fitting.

**Zero-crossing Detection Method** The main method of beam phase measurement is the rising-edge sampling of the button BPM signals and calculated by the zero-crossing detection algorithm [6]. Sampling points of the button pickup signal is shown in Fig.4. The longitudinal phase equals the intercept of the time ordinate after linear fitting. To ensure the validity of the algorithm, the longitudinal offset cannot be too larger to prevent the sampling points from exceeding the rising edge threshold.

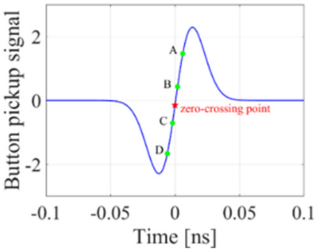

Figure 4: Sampling points of the button pickup signal.

**Two-frequency Method** The main method of measuring beam longitudinal length is two-frequency method [7].

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Since enough signal amplitude and RF component limitation, we chose the baseband and 6th harmonic sidebands (about 500MHz and 3GHz) as working frequencies. The bunch length calculation formula is as follows:

$$\sigma = \sqrt{\frac{2}{m_2^2\omega_0^2 - m_1^2\omega_0^2}\ln(K_1\frac{V_1}{V_2} + K_2)}\,. \qquad (1)$$

where $m_2$, $m_1$, $\omega_0$ are theoretically knowable, and the ratio of $V_1$ to $V_2$ is measured from the two-frequency system. Due to two channels transfer functions difference and limited bandwidth, two coefficients $K_1$ and $K_2$ are introduced into the equation. No theoretical analytic solution for $K_1$ and $K_2$ and the two coefficients can be calibrated by Streak Camera

## SYSTEM SETUP

The system framework of the 6D bunch-by-bunch diagnostic system (as shown in Fig.5), which can be used to measure beam transverse size, position, longitudinal phase and length, simultaneously. The data acquisition system is composed of four ADQ digitizers, which has four input channels with a 14-bit ADC, 1.2GHz analogue bandwidth, maximum 1GS/s sampling rate and multi-board synchronization. The synchronous sampling mainly relies on the same clock and trigger from the timing system.

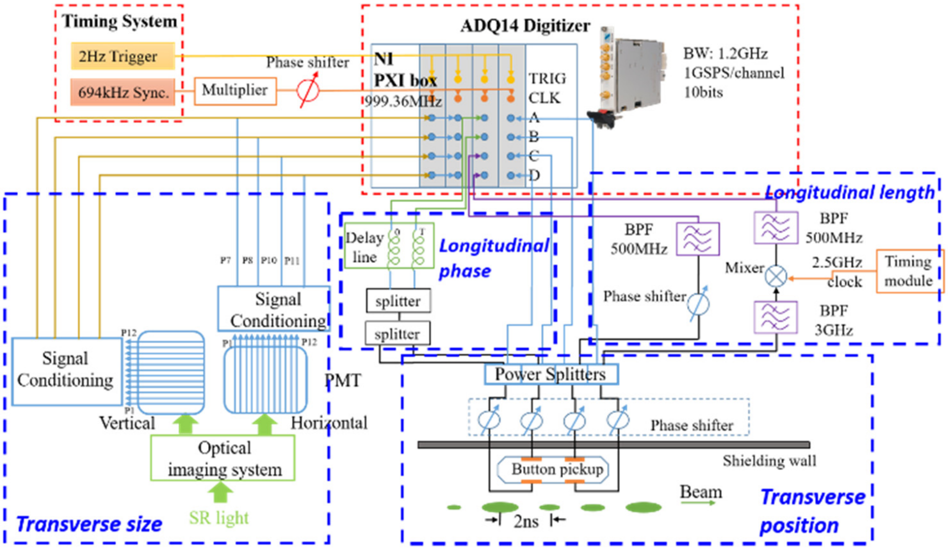


Figure 5: System framework of the 6D bunch-by-bunch diagnostic system.

### Beam Transverse Position Subsystem

Beam transverse position subsystem consists of button BPM, adjusted phase shifters and signal acquisition digitizer. The beam position information is obtained from the Button BPM. And it adds four phase shifters to ensure the phase coherence of the pickup signals. Also, it adds a phase shifter in the clock channel, which is used for phase adjustment of the clock signal to ensure the peak of sampled signals. Meanwhile, in order to facilitate the use of ADQ digitizer, the clock signal is multiplied to 1GHz by the multiplier module.

### Beam Longitudinal Phase Subsystem

Beam longitudinal phase subsystem also consists of button BPM, adjustment phase shifters and signal acquisition digitizer. The beam phase information is obtained from the sum signal of the Button BPMs, which can eliminate the transverse effects. It also has a phase shifter in the clock channel, but the purpose is to ensure the zero-crossing point of the sampled signals. At the same time, the system realizes sampling with the same time interval using four delay lines (typical T=100ps).

### Beam Transverse Size Subsystem

SR light signal from the optical imaging system is captured by a high-speed PMT array (Hamamatsu H10515B) with 16 channels of 0.6ns rise time. An analogue front-end board has been designed for fast signal pick-up of photomultiplier array detector, which converted plug pins to SMA connector. Four amplifiers (Hamamatsu C5594) with wide bandwidth (50k-1.5GHz) and high gain (36dB typ.) are used to condition signals.

### Beam Longitudinal Length Subsystem

The beam signal derived from the button BPM is divided into two channels by a 2-way power splitter. One channel passes through a 500MHz band-pass filter (BPF) as one working frequency. On the other channel, 6-th harmonic frequency is picked up as another working frequency. A mixer with 2.5GHz local oscillator (LO) signal from a timing module is used to output an intermediate frequency of 500MHz from the filtered 3GHz signal.

## PERFORMANCE EVALUATION

### *Charge(Q)*

The bunch charge can be obtained from the peak value of the button BPM or the SR light. Results from different subsystems are consistent with each other. In the extraction of refilled bunch, the stored bunch is obtained from the averaged charge from all stored bunches. And the refilled bunch charge is equal to the charge after injection minus the charge before injection.

The performance evaluation is based on the daily operation. The total current is 230mA with uniform filling mode.

### *Transverse Position (x, y)*

The principal component analysis (PCA) method is used to evaluate the measurement uncertainty of transverse position. Two modes above the noise floor stand for synchrotron oscillation coupled by dispersion. Therefore, the amplitude of noise floor can be used to identify the system resolution. Figure 6 shows the position resolution, which is better than 10um with 0.6nC.

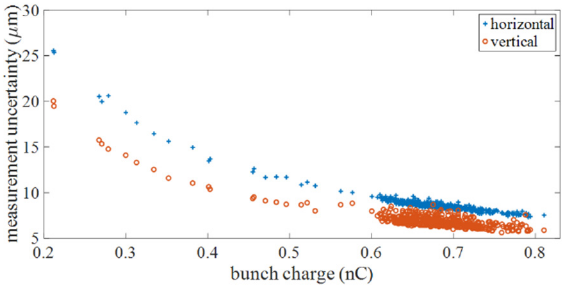


Figure 6: Resolution of the transverse position measurement.

### *Longitudinal Phase (z)*

The same method is used to evaluate the longitudinal phase. Figure 7 shows the results of the phase uncertainty. The phase resolution is better than 0.8ps with 0.6nC.

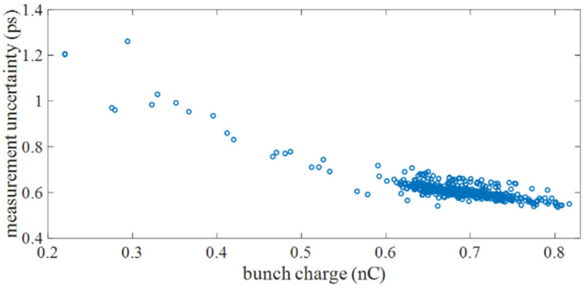
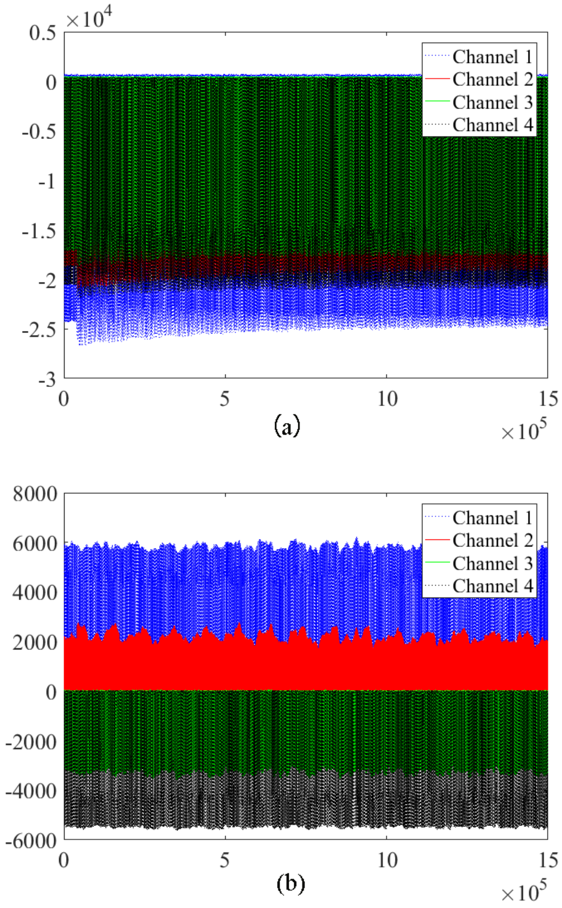


Figure 7: Resolution of the longitudinal phase measurement.

## EXPERIMENTAL RESULTS

An ideal beam experiment involves adjusting the machine parameters, and then compare the measured value with the expected value. It is difficult due to the lack of machine research time. However, the injection transient process is frequently observed in the user operation mode at SSRF. After injection, the injected bunch oscillated around the stored bunch in the three dimensional space, which induced the damping betatron oscillation due to the timing mismatch of kickers and the damping synchronous oscillation due to the phase mismatch of the refilled charge.

The experiment carried out during the daily operation mode, but the data was captured after injection. The raw data were obtained by the ADQ digitizers simultaneously (as shown in Fig.8). A slight amplitude increase can be seen in the 56-th turns of the position data and then tends to flat after thousands of turns.



(a)

(b)

Figure 8: Raw signal data (a) of the beam position measurement (b) of the beam phase measurement.

### *Refilled Bunch Position and Phase Extraction*

We sampled the negative peak of the BPM signal in the transverse position measurement and sampled four points around the zero-crossing point of the BPM sum signal in the longitudinal phase measurement. Since the bunch length of the stored charge is unchanged during the injection process, we omitted the measurement of longitudinal length and only focus on the four parameters ($x$, $y$, $z$, $\sigma x$) measurements in the following experiments.

The charge weighted average method is used to extract the transverse position and longitudinal phase of the refilled bunch. After extraction, the horizontal displacement oscillation of the stored bunch and the refilled bunch can be obtained, as shown in Fig.9. An obvious damping betatron oscillation can be seen in the refilled bunch and the maximum oscillated amplitude is almost 10mm.

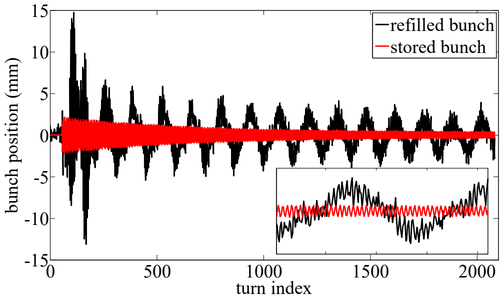


Figure 9: Transverse position extraction of the refilled bunch.

Similar with the refilled bunch position extraction, the refilled bunch phase is shown in Fig.10. The maximum oscillation amplitude is approximately 100ps to 200ps.

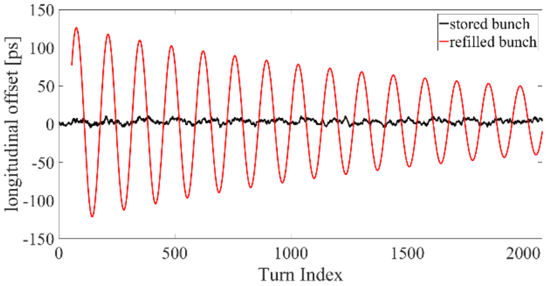


Figure 10: Longitudinal phase extraction of the refilled bunch.

### *Impedance and Wake-field Analysis*

The betatron oscillation of the bunches was introduced by two sources: the mismatch of the injection kicker field, and the wake-field effects of the previous bunches. The PCA method was used to separate the oscillation modes to more clearly analyse the oscillation of each component. Figure 11 shows the separation results of the beam position, mode-1 expressed as a typical damping oscillation, mainly contributed by the mismatch of the kickers. Mode-2,3,4 are all affected by kicker mismatch and wake-field effects.

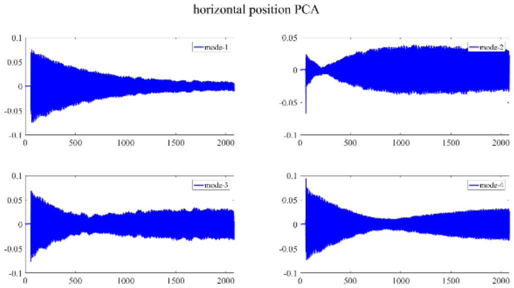


Figure 11: The first four principal components of the oscillation after injection.

Each bunch exhibited different position oscillation amplitude as different contributions from the two parts. As shown in Fig.12, the largest oscillation occurred at bunch #397, whereas the smallest oscillation occurred at bunch #3. The turn-by-turn position oscillation behaviours of these two bunches in the time domain are shown in Fig.13.

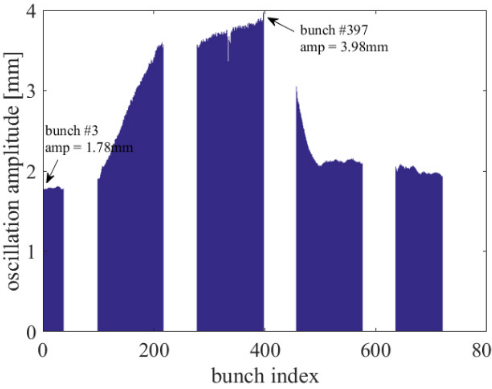


Figure 12: Initial position oscillation amplitude of each bunch.

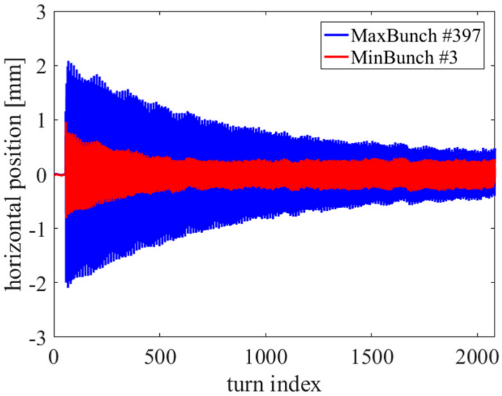


Figure 13: Turn-by-turn position oscillation of bunch #397 and bunch #3 in time domain.

Analysis with the same method, the qualitative bunch size and bunch position results can also be obtained from the transverse size subsystem, as shown in Fig.14. The size results were also the combined effects of the kicker field mismatching and wake-field, and were in good agreement with the position results.

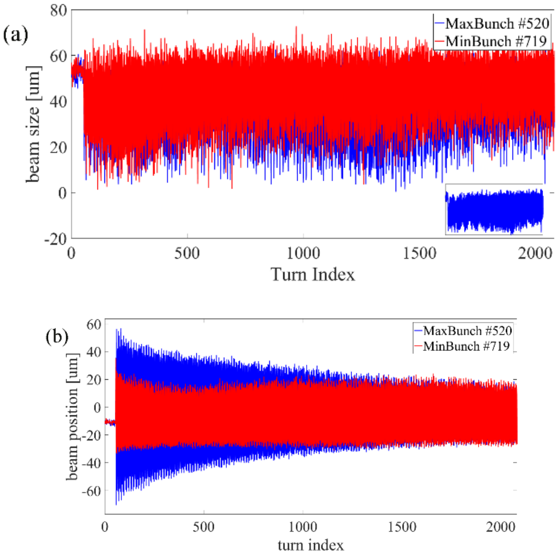


Figure 14: Turn-by-turn position and size oscillation measured by the transverse size subsystem (a) bunch size result, (b) bunch position result.

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## CONCLUSIONS

The 6-dimensional diagnostic system with bunch-by-bunch capability is successfully implemented at SSRF. The transverse position and size, and the longitudinal phase and length during the injection transient process are all measured by the system. After the refilled bunch extraction algorithm, transverse position and longitudinal phase of the refilled bunch can be obtained. And the dynamic parameters of the storage ring also can be obtained from the injection transient study. DAQ need to be upgraded and intelligent trigger mode based on FPGA will be implemented. After upgrading, this system will be more useful for physicist to capture bunch-by-bunch data when unstable beam condition shows up.

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