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THREE-DIMENSIONAL BUNCH-BY-BUNCH POSITION MEASUREMENT AT SSRF*

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Abstract

Measurement of the bunch-by-bunch particle beam position related to dynamic instability is a useful input to accelerator optimization. And the bunch-by-bunch information has been contained in the BPM signals, including bunch charge, transverse position and longitudinal phase information. This paper reports a 3D beam position monitor system based on a high speed digital oscilloscope, which has been used to capture three-dimensional position information during the injection transient at the Shanghai Synchrotron Radiation Facility. With this information the traces of stored bunch and refilled bunch, and the mismatch of energy, transverse position and longitudinal phase between them can be precisely retrieved. The progress of this work and several particular experimental results will be discussed in this paper. The details of data processing method so-called software re-sampling technique will be discussed as well.

INTRODUCTION

In the operation of the third generation light source, the beam instability will be caused by rail noise. The beam instability, such as beam position shift, beam tune drift and beam wake field effect, will affect the effective operation of the accelerator. In the SSRF (Shanghai synchrotron radiation facility), turn-by-turn beam position measurement has been realized and the resolution has reached 2 μm [1]. In order to improve the resolution, it is important to measure the beam position bunch by bunch. At the same time, higher resolution is essential for the study of beam position shift and the mismatch of energy during the injection transient process. In this paper, the traces of the stored bunch and refilled bunch can be achieved. And the three-dimensional beam motion can be constructed according to the three-dimensional position information. The beam position can be obtained from the amplitude difference among four signals extracted by the button electrode. The difference-over-sum method is usually used in the beam transverse position measurement. However, in the longitudinal phase measurement, the bunch phase is detected from the difference between a beam pulse and a reference frequency signal. In this paper, the longitudinal phase is calculated by using the zero-crossing fitting method. Since the original signal of the storage ring button electrode already contains the transverse position and longitudinal phase information, the original signal can be extracted directly by a high sampling rate oscilloscope. The three-dimensional bunch-by-bunch position information was calculated by the off-line data processing. Shanghai light source as the third generation synchrotron radiation source, the storage ring energy reached 3.5 GeV with 432 m in circumference. There are totally 140 BPMs (Beam Position Monitor) around the storage ring. For SSRF, a practical filling pattern is a 500 –bunch train filled in the storage ring, leaves a 220 bucket empty gap. The harmonic number is 720 and the RF frequency is 499.654 MHz.

PRINCIPLE

Typical BPMs used in the storage ring are button-type electrode and strip-type electrode. When the beam passes through the button electrode, the electric quantity obtained by each electrode is closely related to the distance from the surface of the button electrode to the beam due to the electrostatic induction. The three-dimensional position information of the beam can be calculated from the original signal outputted from the electrode. Figure 1 shows the cross section of the button electrode used in the Shanghai light source storage ring. For the non-center bunch response, the amount of induced charge on the electrode is different when the bunch whose current is $I_b(t)$ passes through the non-center position of the button electrode. As shown in Fig. 1, the bunch is in the (δ, θ) position, the radius of the vacuum chamber is b, and the distance from the electrode to the vacuum chamber is a.

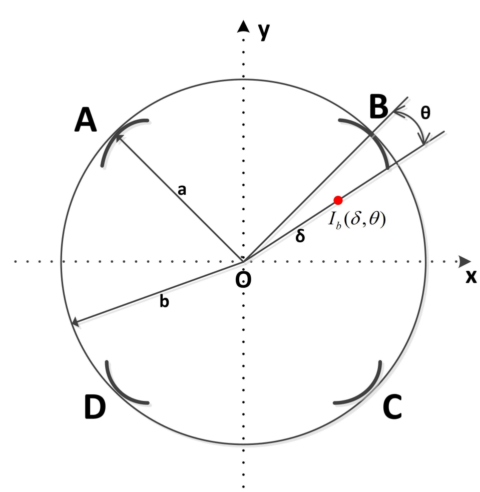

Figure 1: Cross section of button-type position monitor.

In the following analysis [2], a Gaussian distribution of the beam is used. Considering N particles of charge e in a bunch of the half width σ, the induced voltage generated by

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the bunch on the electrode is:

$$V_b(t) = \frac{\pi a^2 Z}{b\beta c} I_n 2 f_0 A sin(\omega_s t + \phi) \times \times \exp^{in\omega_0(t+Acos(\omega_s t+\phi))} F(\delta,\theta), \quad (1)$$

with

$$I_n = I_0 \exp^{-\frac{n^2\omega_0^2\sigma^2}{2}}, \quad (2)$$

$$I_0(t) = \frac{eN}{\sqrt{2\pi}\sigma} \exp(-\frac{t^2}{2\sigma}). \quad (3)$$

And the position information is:

$$F(\delta,\theta) = \frac{a^2-\delta^2}{a^2+\delta^2-2a\delta cos\theta}, \quad (4)$$

$$\delta = \sqrt{x^2+y^2}, \quad (5)$$

$$\theta_{A,B,C,D} = \frac{m\pi}{4} - tan^{-1}(\frac{y}{x})(m = 3,1,7,5). \quad (6)$$

When the geometrical shape of the probe is determined, the electrode induced voltage is related to the two parts of information. One is the beam intensity I_0 and the bunch length σ, and the other part is the transverse position F(δ,θ) and longitudinal phase ϕ of the bunch through the button electrode. The original signal of the button electrode can be extracted by using the bunch-by-bunch 3D beam position monitor system based on a broadband oscilloscope, which contains information such as the bunch charge, transverse position and longitudinal phase. Bunch charge can be derived by measuring peak voltage of sum signal, which has been measured in the Shanghai light source [3]. The equivalent beam position is obtained from the amplitude difference among four signals by difference-over-sum processing (Δ/Σ). In the transverse position measurement, the result of the measurement is that the stored bunch mixed with the refilled bunch. It is necessary to separate the refilled bunch from the stored bunch by off-line data processing. It is known that the measured sum signal is:

$$X_m = k_x \frac{\Delta m}{\Sigma m} = k_x(\frac{\Delta s + \Delta r}{\Sigma s + \Sigma r}), \quad (7)$$

where k_x is the compensation coefficient. Δs, Σs are the difference signal and sum signal of the stored bunch, and Δr, Σr are the difference signal and sum signal of the refilled bunch. Then the refilled signal from the measured signal can be got by:

$$X_r = \frac{\Sigma s}{\Sigma r}(X_m(1+\frac{\Sigma r}{\Sigma s}) - X_s). \quad (8)$$

As the beam signal is related to the amount of charge, the type can be simplified as:

$$X_r = \frac{Q_s}{Q_r}(X_m(1+\frac{Q_r}{Q_s}) - X_s). \quad (9)$$

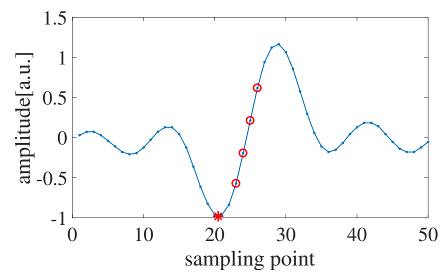

Figure 2: Sampling points in the position measurement.

In order to improve the accuracy of beam position measurement, this paper measured the negative peak of the button electrode signal to obtain the beam transverse position. The sampling points is shown in Fig. 2 (red star).

Since the RF frequency is 499.654 MHz and the sampling rate of the oscilloscope is 25 GHz, it cannot obtain the peak voltage directly from the measurement signal. A so-called software re-sampling technique based on cubic spline interpolation algorithm has been performed in the SSRF [4]. It is necessary to obtain the exact time interval $T_r f$ between two bunches. A FFT algorithm was used to obtain the RF frequency. To improve the measurement precision, zero-padding method was used to extended the data length to the integer powers of two. Because the length of the signal cable from four electrodes to the oscilloscope is not exactly equal and the sampling clock of each channel is not synchronous, the first peak point was chosen as the starting point for each channel. Then the bunch-by-bunch BPM signal could be obtained from the raw waveform data with the sampling interval $T_r f$. At the same time, this method can be also used in the longitudinal phase measurement. To improve the accuracy of phase measurement, four sampling points at the zero-crossing point is chosen for phase calculation. By linear fitting, the bunch phase can be obtained by the intercept with the timeline, as shown in Fig. 2 (red circle).

EXPERIMENT

The experiment is performed during the injection process. Particles will generate an obvious oscillation in the injection transient process. It is important for the optimization of our accelerator and the study on the injection process if the three-dimensional position displacements can be observed. In the experiment, three-dimensional displacement results have been obtained. Figure 3(upper) shows the horizontal displacement, it can be seen that a small oscillation in the stored bunch and the refilled bunch oscillate around the stored bunch. Figure 3(lower) shows the vertical displacement, compared with the horizontal displacement, the vertical oscillation amplitude is much smaller and the oscillation of the stored bunch is almost zero.

At the same time, the longitudinal phase shift also can be detected by the 3D position monitor system. From Fig. 4, a regular oscillation can be achieved. The longitudinal position displacement is 200 ps in the storage ring. And it is not symmetrical relative to the stored bunch. If we magnify

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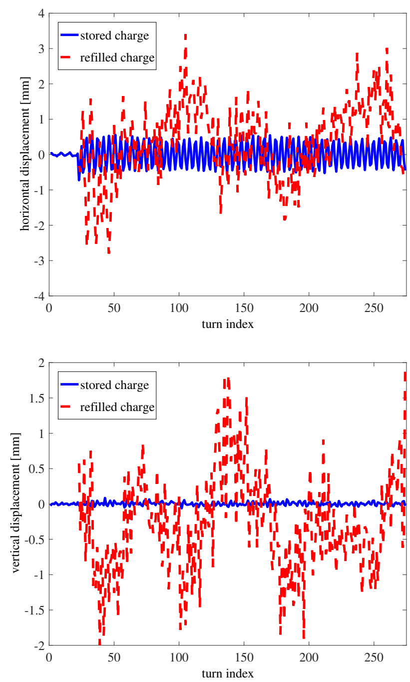

Figure 3: Transverse displacement of the injected bunch. Upper is the horizontal displacement and lower is the vertical displacement.

the picture, as shown in Fig. 5, the details in longitudinal displacement of the stored bunch can be observed. The stored bunch still make a small range oscillation and the peak displacement is just several picoseconds.

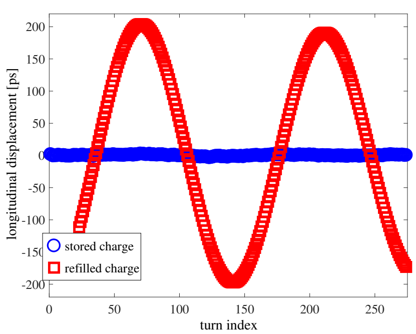

Figure 4: Longitudinal oscillation displacement of the injected bunch.

On the other hand, the beam tune can be also measured by the frequency spectrum of the injected bunch. From Fig. 6, it shows that the transverse tune is (0.22 , 0.30) and the longitudinal tune is 0.007

CONCLUSIONS

A bunch-by-bunch 3D position monitor system has been developed in the SSRF. Three-dimensional position information can be measured directly from the button electrodes.The refilled bunches have been separated from the stored bunches.

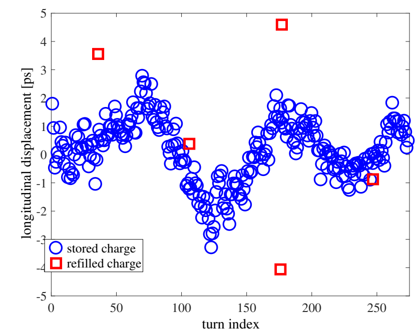

Figure 5: Details in longitudinal displacement of the stored bunch.

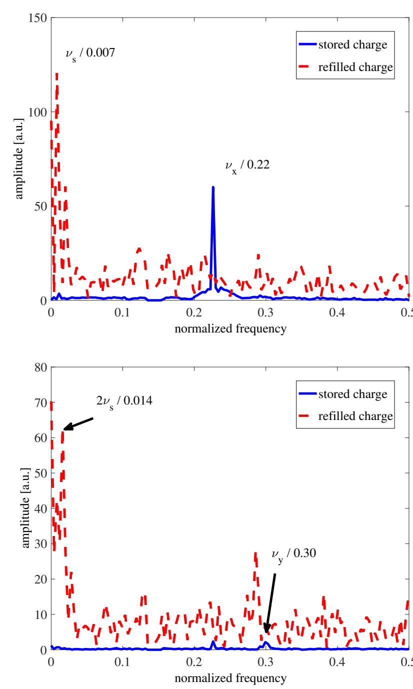

Figure 6: Frequency spectrum of the injected bunch.

During the transient injection process, the refilled bunches oscillated around the stored bunches. The transverse displacement of the refilled bunches is about 2 mm and the longitudinal displacement is 200 ps.

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