BUNCH PHASE MEASUREMENT FOR STORAGE RING*

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Abstract

A bunch-by-bunch phase measurement system has been studied to improve the accuracy of phase measurement. Longitudinal phase information will be retrieved from beam signals picked up from the button electrodes. The signals from four electrodes in the BPM are summed by using a 4-way power driver, by which the effect of the transverse beam offset on the phase measurement can be eliminated. Four samples with fixed time interval (typical 100ps) for each bunch, which are taken by a 500MHz waveform recorder with a four channels signal splitting and delaying network, will be used to calculate bunch phase. In this paper, we present the layout of the system and primary experimental results.

INTRODUCTION

Shanghai synchrotron radiation facility (SSRF), as a third generation light source, started user operation since April 2009 [1]. The SSRF consists of a 150MeV linear accelerator, a 3.5GeV booster synchrotron, a 3.5GeV storage ring and phase -I seven beamlines. About 500 bunches will be stored with 2ns spacing in the storage ring, where the harmonic number is 720. The RF frequency is 499.654MHz. In order to take full advantage of SSRF, the phase-II project had been proposed since 2011, 16 beam lines would be built and the electron storage ring would be upgraded. Lots of insertion devices with small gap would be increased, which would introduce beam instability.

Couple thousands of beam diagnostics experiments have been performed during past eight years, including charge, lifetime, transverse position and beam length. Measuring the longitudinal phase is also important to investigate the longitudinal beam dynamics. The longitudinal phase is usually detected from the phase difference between a beam pulse and a reference frequency signal. Various techniques to detect beam longitudinal phase have been employed in circular accelerators, such as a digital oscilloscope with high sampling rate at LNLS [2], a phase detector at Spring-8 [3] and a commercially Libera unit is also used for beam phase measurement at ESRF [4]. All of these methods measure the averaged beam phase. In order to increase the stability of the beam and study the dynamic of the injected bunch, we need to perform the bunch-by-bunch phase measurement.

In this paper, a new bunch-by-bunch phase measurement system based on the button BPM pickups and the 500MHz waveform recorder has been developed. The designs of the system and some distinctive results are presented in section 4.

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BASIC IDEA

As a common diagnostic component in an electron storage ring, a four button BPM pickup carries the information of beam position, intensity and longitudinal phase. Assuming the RF signal was in sine distribution, in order to measure the bunch phase, the pickup signal is adjusted so that it samples the slope at the zero-crossing of the RF pulse, as show in Fig. 1. A change in bunch phase is then transformed into an amplitude change of the RF pulse. By linear fitting, the bunch phase can be obtained by the intercept with the timeline.

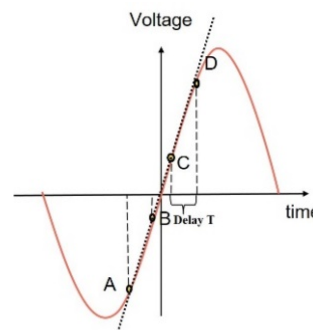

Figure 1: Principle of the phase calculation.

On the other hand, a IQ (In-phase and Quadrature phase) sampling method was usually used to direct process high-frequency signals, which allow to measure the amplitude and the phase of beam signals with a reference signal [5]. When four samples with 500ps interval, the phase difference between them is 90°, a IQ sampling algorithm can be used to calculate bunch phase. The IQ sampling method get the amplitude exactly, so it is good enough to calculate individual bunch phase. Assuming input signals are sine function:

$$x(t) = A\sin(\omega t + \varphi) \,. \tag{1}$$

The IQ signals are given by:

$$\begin{aligned} I &= (x_A - x_C)/2 \\ Q &= (x_D - x_B)/2 \end{aligned} \,. \tag{2}$$

When the four signals sampling consecutively with 90° in phase, the signals are as follows:

$$\begin{aligned} x_A &= A\sin\theta \quad x_C = -A\sin\theta \\ x_B &= A\cos\theta \quad x_D = -A\cos\theta \end{aligned} \,. \tag{3}$$

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Then we can get the IQ signals according to Eq.2, and the phase difference between the beam signal and the reference RF can be given from the ratio V_I / V_Q by

$$\theta_b - \theta_{RF} = -\tan^{-1}\left(\frac{V_I}{V_Q}\right) \quad (4)$$

where the θ_{RF} is constant.

SIMULATION

The simulation work about comparison and error analysis of the two methods have been accomplished. When the noise levels of signal from one per thousand to one tenth, we simulate the phase measurement uncertainty of the zero-crossing detection method and the IQ sampling method. Fig.2 shows the phase measurement uncertainty simulation of the zero-crossing detection method. From Fig.2 we can know, when the noise of signal is less than one percent, the relative uncertainty of measurement is better than 1ps. And smaller the time interval, better the measurement uncertainty. But the time interval between samples has little impact at 500MHz sample rate.

The IQ sampling method can get the amplitude of signal exactly, so this method is often used to calculate the charge of the bunch. Fig.3 shows the phase and amplitude measurement uncertainty simulation of the IQ sampling method. Similar to the zero-crossing detection method, the relative uncertainty of measurement is also better than 1ps, when the noise is less than one percent.

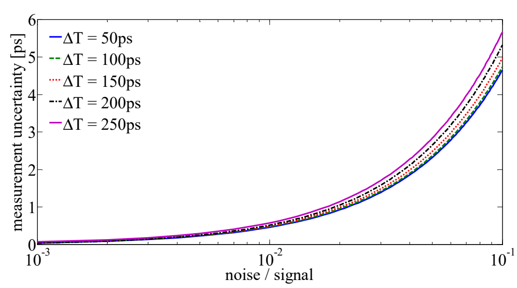

Figure 2: Phase measurement uncertainty simulation of the zero-crossing detection method.

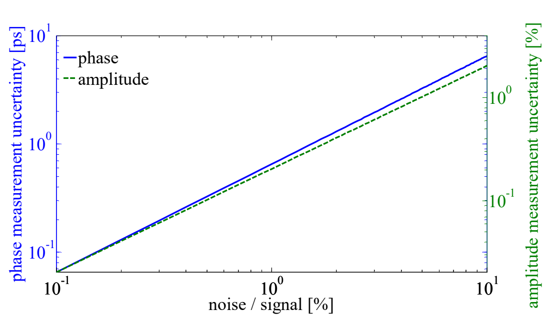

Figure 3: Phase and amplitude measurement uncertainty simulation of the IQ sampling method.

However, the RF frequency (500MHz) is variable, there will be a system error when the RF frequency changes. Fig.4 shows that, when the RF frequency changes from 499.5MHz to 500MHz, the measurement error is less than 0.5ps, which is small enough to ignore.

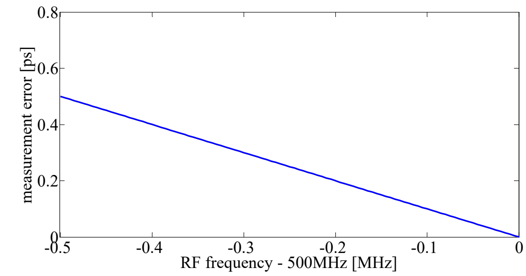

Figure 4: System measurement error when the RF frequency changes.

EXPERIMENT

The experiment is based on the platform of SSRF. And the filling pattern of injected beam for user operation mode has been defined as 260mA average current. We performed zero-crossing detection method and IQ sampling method to realize the bunch-by-bunch phase measurement.

Hardware

The bunch-by-bunch phase measurement system consists of four BPM pickups, analog front-end, and a 500MHz waveform recorder. Fig.5 shows its block diagram.

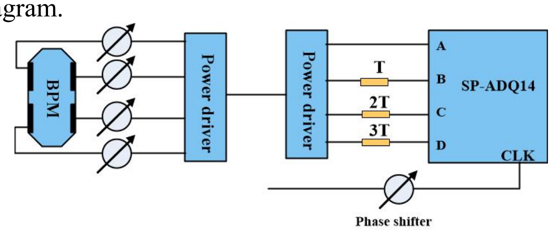

Figure 5: Hardware block diagram of the bunch-by-bunch phase measurement system.

Beam bunches are sensed by BPM buttons at SSRF, and the bunch signals are fed into a power driver (4 to 1, BW 1-1000 MHz), by which the effect of the transverse beam offset on the phase measurement can be eliminated. Then the summed signal split into four pulses with a fixed interval. To satisfy bunch-by-bunch analysis requirement an ultra-high speed ADC, practically SP-ADQ (4 analog channels,14-bit, 0.5GSPS sample rate per channel, external clock), is adopted as waveform digitizer. The trig signal is 2 Hz. And the waveform recorder takes 2500000 samples (720 bunches,3472 turns) continuously.

Zero-crossing Detection Method

Since the beam spacing is 2ns, one sample for each bunch achieved in a 500MHz RF reference signal. In this paper, two tests have been done with different intervals (80ps and 180ps). On running a Linux EPICS IOC core, the CPU acquires a bunch by bunch waveform via

500MHz sampling [6]. The signal voltages (V_A V_B V_C and V_D) and the time interval (T) will be used to calculate the bunch phase by linear fitting. And the resolution of bunch phase measurement is show in Fig. 6, which is better than 1ps.

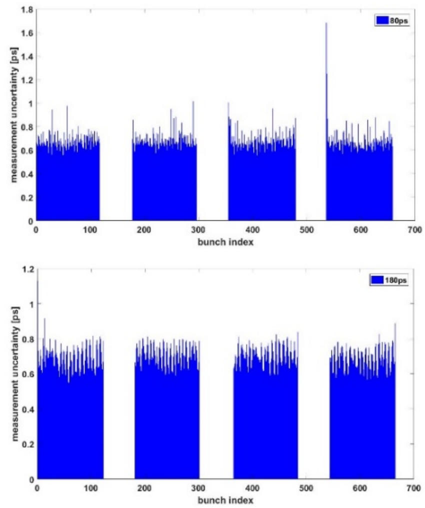

Figure 6: Resolution of bunch phase measurement of 80ps interval (up) and 180ps interval (down).

IQ Sampling Method

Zero-crossing sampling method have to sample at the zero crossing point of the RF pulse. The disadvantages of this method are that the range of sampling phase variation is much small and it cannot get the voltage exactly. Therefore, we adopted another method, as seen in Fig. 7. Four samples of each channel with 500ps interval is 90° phase difference. Sampling the four channels during safety injection. Then we can get the exact voltages of the four samples and calculate the bunch phase by I/Q sampling method. On the other hand, we increased a band-pass filter (central frequency 500MHz, BW 300MHz) between two power drivers so that the bunch signal closer to a sine wave. Compared with the zero-crossing detection method, the sampling range of this method is enormous and it can infer the maximum amplitude range. The resolution of bunch phase measurement of 90 ° phase difference when safety injection is show in Fig. 8, where the resolution of longitudinal phase is about 1ps.

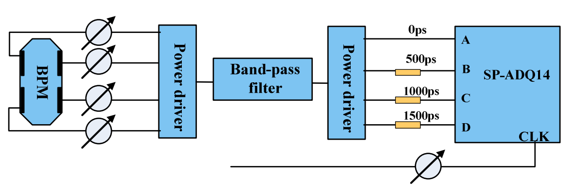

Figure 7: Hardware block diagram of 90 ° phase difference measurement system.

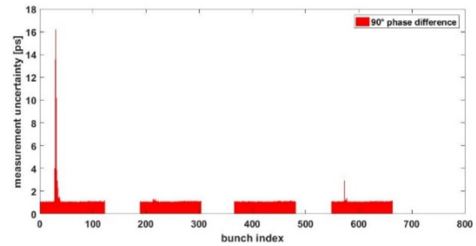

Figure 8: Resolution of bunch phase measurement of 90° phase difference.

Horizontal positions of the injected bunch had been found at SSRF [7]. Besides, the phase transient state of injection can be captured in this experiment. The longitudinal offset of the injected bunch separated from the stored one is shown in Fig.9. At the first glance, the behaviour of the stored bunch (black line) is considered trivial, while the motion of the injected one (red line) shows oscillation damping, obviously.

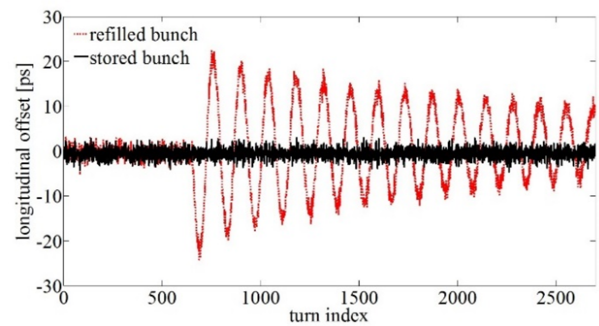

Figure 9: Longitudinal offset of the injected bunch separated from the stored one.

CONCLUSIONS

The beam phase measurement system based on waveform recorder was implemented in the storage ring at SSRF, which can detect longitudinal phase at bunch-by-bunch rate. The resolution of longitudinal phase was better than 1ps. This system demonstrated distinctive features different from usual phase measurement system. The phase oscillation during injection can be captured. And bunch charge measurement can be obtained from the IQ sampling method.

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