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BUNCH-BY-BUNCH BEAM LENGTH MEASUREMENT USING TWO-FREQUENCY SYSTEM AT SSRF*

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Abstract

A Two-frequency method has been implemented for bunch length measurement at Shanghai Synchrotron Radiation Facility (SSRF). It is based on the information from two harmonic frequencies of Flourier Transformation of longitudinal charge distribution. We select 500MHz and 3GHz as working frequency and the system consists of power splitters, band-pass filters and a mixer. Raw data are acquired by a digital oscilloscope and analyzed by MATLAB code. The system has been calibrated by Steak Camera in single-bunch experiment environment with bunch charge from 0.23nC to 6.05nC. The paper also shows bunch length synchronous oscillation phenomenon during injection period.

INTRODUCTION

Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation light source facility in Shanghai ,China, which has been operating about 8 years. With the second phase construction and more inserts in storage ring, the longitudinal instabilities will raise up including bunch-length diversity. Moreover, bunch length should be regulated within appropriate ranges for high brilliance pulses producing, which leads it as an important factor of overall beam performance.

Bunch length is now precisely measured by Streak Camera in SSRF with bunch-by-bunch capability and resolution of 2 ps [1]. However, the data reputation rate of Streak Camera is low about 2 Hz, and it requires complicated optical structures. A two-frequency system for bunch-by-bunch bunch length measurement has been implemented in SSRF for real-time measurement and data analysis of SSRF daily operation.

The two-frequency method picks up longitudinal distribution information from Beam Position Monitors (BPMs).The bunch length could be calculated through the intensity radio at two harmonic frequencies of Fourier component in Gaussian longitudinal charge distribution.It is a indirectly way in Frequency domain and had been used for average bunch length measurement at CERN with a resolution about 0.7 ps [2].Bunch-by-bunch data acquisition and analysis techniques have been developed at SSRF for many years with successfully implemented for position measurement [4] [5].It could also applied for the two-frequency system to approach bunch-by-bunch results.

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Two harmonic frequency detection point is selected as 500 MHz and 3 GHz in the two-frequency system. It employs radio-frequency (RF) electronics, a high sampling rate and multi channels oscilloscope as data acquisition module. Data analysis is under Matlab environment. In this paper, we will discuss the principle, system setup, system calibration using Streak Camera and bunch length synchronous oscillation phenomenon during injection period.

PRINCIPLES

A typical bunch longitudinal charge distribution is Gaussian and its Fourier component of m_i-th harmonic is given as:

$$V(m_i\omega_0) = 2V_0 exp\ -\frac{m_i^2\omega_0^2\sigma_0^2}{2} \tag{1}$$

where ω_0 is the RF frequency 499.654 MHz of SSRF, V_0 is the DC component, σ_0 is the bunch length considered as a constant at one time. Hence, the σ could be obtained with voltage radio between two different harmonic frequency points as follows:

$$\sigma = \sqrt{\frac{2}{m_2^2\omega_0^2 - m_1^2\omega_0^2} ln\left(\frac{KV_1(m_1\omega_0)}{V_2(m_2\omega_0)}\right)} \tag{2}$$

where V_1 and V_2 are experimental measured value at two m_i-th harmonic frequencies, m_2 is larger than m_1 and K is a coefficient calculated by two-frequency results. To calculate the resolution of bunch length σ, we could get the equation as follows:

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{2}}{\left|m_1^2 - m_2^2\right|\omega_0^2\sigma^2}\left[\left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta V_2}{V_2}\right)^2\right] \tag{3}$$

The $\Delta V/V$ is equal to the signal-to-noise ratios(SNR)of V_1 and V_2 signal, which are close enough at most occasions. From Eq. (3), the resolution of bunch length will suffer a severe enlargement when the two frequencies are too close: $\left|m_1^2 - m_2^2\right| \to 0$. As RF components bandwidth limitation, m_1=1 and m_2=6 (about 500 MHz and 3 GHz) are selected for this application.

SYSTEM SETUP

The two-frequency bunch-by-bunch bunch length measurement system is comprised of RF conditioning module, time module and real-time oscilloscope acquisition module, the detail block diagram is shown in Figure 1.

The signal from BPM button is divided into two channels by a two-way zero-degree power splitter. One channel passes

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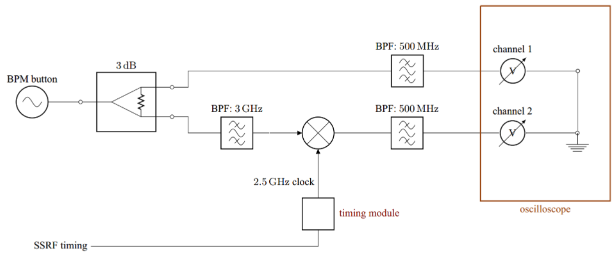

Figure 1: Block diagram of two-frequency bunch length measurement system [3].

through a 500 MHz band-pass-filter (BPF) as one working frequency. On the another channel, the raw signal meets a 3 GHz BPF, which picks up the 6-th harmonic frequency as working frequency. A mixer with 2.5 GHz local oscillator (LO) from clock module transport the 3 GHz signal to a intermediate frequency of 500 MHz for bandwidth limitation acquisition of oscilloscope. After the same 500 MHz BPF, it is acquired by the oscilloscope with the first channel at the same trigger. Time delay between channels are strictly correction by oscilloscope deskew function. The photograph of RF electronics are shown in Figure 2.

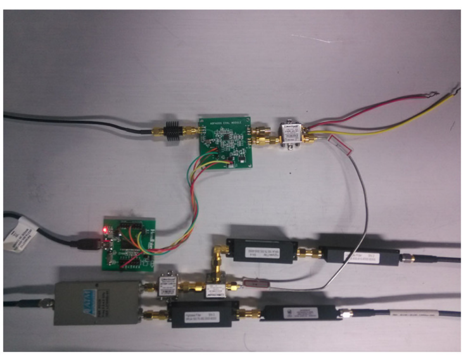

Figure 2: The photograph of RF electronics [3].

CALIBRATION IN SINGLE-BUNCH PATTERN

Equation Correction with Bandwidth Effect

The bunch length calculation equation in Eq. (2) is derived in ideal two dot frequency environment. Actually, the RF bandwidth in electronic are inevitable, which contributes a constant offset. The equation is corrected below as Eq. (4) and following calibration will be based on it.

$$\sigma = \sqrt{\frac{2}{m_2^2\omega_0^2 - m_1^2\omega_0^2} ln\left(K_1 \frac{V_1}{V_2} + K_2\right)} \quad (4)$$

The variables in Eq. (4) V_1/V_2 is considered as an entirety as R_{12} for simply calculation and coefficients K_1 and K_2 fitting.

Bunch Length Results from Streak Camera

Streak Camera is a usual absolute bunch length measurement method with resolution of about 2 ps and regarded as the reference in our application.In the experiment, the bunch charge enhances from 0.23 nC to 6.05 nC, which is covered the SSRF operating status and up to a high unstable level. The typical four results from Streak Camera at four different currents is shown in Figure 3. The relationship between bunch charge and bunch length is shown in Figure 4. From the bunch length enhanced performance along bunch charge raised up by Streak Camera results in Figure 4, we have a 2-order Polynomial equation below 1 nC bunch charge and a linear equation upon 1 nC. It offers a wide range and precise reference for the two-frequency method calibration.

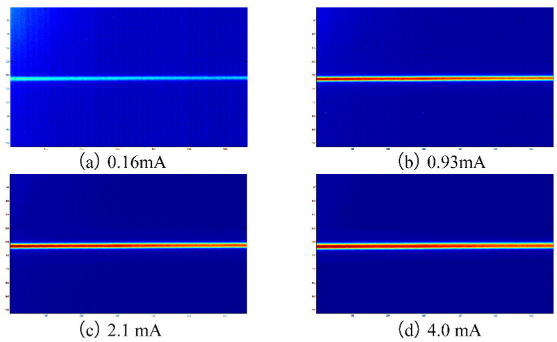

Figure 3: Typical bunch length measured results from Streak Camera.

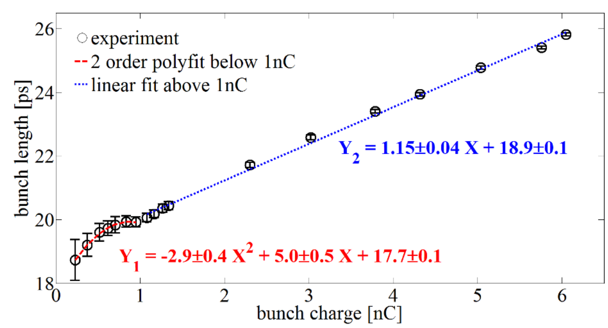

Figure 4: Relationship between bunch charge and bunch length from Streak Camera.

The Two-Frequency Method Calibration Results

The coefficient R_{12} mentioned before could be reckoned by linear fitting between calculated R_{12} and measured R_{12}. The calculated R_{12} comes from truth bunch length value by Streak Camera and the two-frequency method offers the measured R_{12}. Figure 5 presents the relationship and the fitting equation for K_1 and K_2 in Eq.4.

With the calibrated coefficient K_1 and K_2, the two-frequency method also offers absolute bunch length value and could be able to compare with Streak Camera result to evaluate its performance. Figure 6 presents the comparison diagram between this two methods at different bunch charge conditions.

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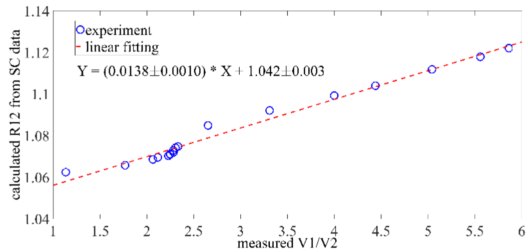

Figure 5: Systemic coefficient calibration.

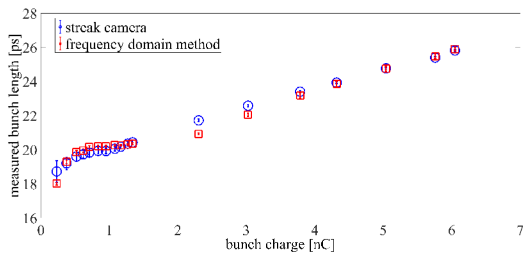

Figure 6: Comparison of bunch length measuring performance between Streak Camera and two-frequency method.

From Figure 6, the two group results keep agreeable generally, even at low charge domain, the two-frequency method shows less deviation than Streak Camera, which demonstrates that Eq. (4) is correct and two-frequency method has the capability of bunch length measurement.

BUNCH LENGTH OSCILLATION DURING INJECTION

There are two kinds of damping oscillation after bunch injection, the betatron oscillation coming from the the timing mismatch of kickers and the synchronous oscillation due to the phase mismatch of the refilled charge, which is combining with the stored charge and a small injected charge. The injected charge oscillate around the stored charge in longitudinal plane, which induces a corresponding bunch length oscillation detected by the two-frequency system. And theoretically, the oscillation frequency will be double of the storage ring synchrotron frequency as phase of injected charge beyond or behind stored charge all contributes bunch length enhanced. Figure 7 shows the behaviors about the betatron oscillation and synchronous oscillation.

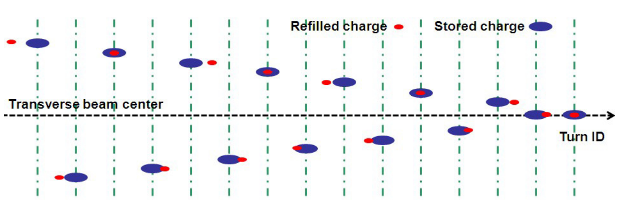

Figure 7: Schematic of two oscillations behaviors after bunch injection [3].

Figure 8 presents bunch length changes in turns after injection contributed by the synchronous oscillation as the blue plots. As a reference, the stored bunch is plotted as well by the red line to demonstrate a stable bunch length status.

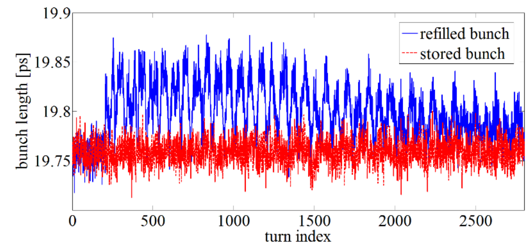

Figure 8: Bunch length changes in turn after injection.

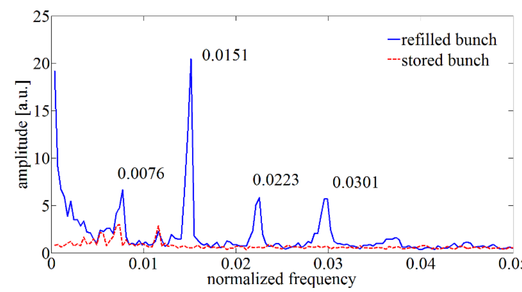

Figure 9: Frequency spectrum of bunch lengths during injection of refilled bunches.

In Figure 8, the bunch length suddenly jumps to a high value, then recover to normal length with damping in thousands turns.We analysis the frequency spectrum of refilled bunch and stored bunch in Figure 9. It could be figured out the synchronous oscillation frequency of SSRF storage ring about 0.0076, and a huge peak at the 2nd harmonic about 0.0151 in Figure 9, which demonstrates our description in Figure 7 about the two oscillation behaviors.

CONCLUSION

The two-frequency method for bunch-by-bunch bunch length measurement has been implemented in SSRF, and successfully calibrated by Streak Camera. The calibration experiments also demonstrates its authenticity and excel-lent resolution in low bunch charge situations. The bunch length oscillations research during injection based on the two-frequency also proves its capabilities in bunch-by-bunch studies. Furthermore, the system will be used for beam loss moment study and other beam phenomenons, or will be served as on-line equipment for real-time bunch length monitoring.

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