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BUNCH LENGTH MEASUREMENT USING MULTI-FREQUENCY HARMONIC ANALYSIS METHOD AT SSRF *

Y.M. Zhou †, Shanghai Institute of Applied Physics, CAS, Shanghai, China
also at University of Chinese Academy of Sciences, Beijing, China
Y.B. Leng#, B. Gao, N. Zhang, Shanghai Advanced Research Institute, CAS, Shanghai, China

Abstract

Harmonics method in the frequency domain is an effective and inexpensive bunch length measurement method, which was implemented at the Shanghai Synchrotron Radiation Facility (SSRF). A multi-frequency bunch-by-bunch length measurement system using an integrated RF conditioning module will be established to reduce the system noise and signal reflection, and to improve the bunch length measurement accuracy as well. The module consists of power splitters, band-pass filters, mixers and so on. The main function of the integrated RF conditioning module is to extract the beam signals at 500MHz, 1.5GHz, 2GHz, and 3GHz operating frequency. Raw data are acquired by a high-precision digitizer and analyzed by MATLAB code. The absolute bunch length can be obtained with a streak camera, which was used to calibrate the response coefficients of the system. Bunch-by-bunch length can be measured by the multi-frequency harmonic analysis method from the button BPM.

INTRODUCTION

SSRF is a third-generation light source that has stable and brilliant synchrotron radiation due to its operation under top-off mode. The harmonic number is 720 and the RF frequency is 499.68MHz. Four bunch trains with 500 bunches of 2ns spacing were filled in the storage ring.

The bunch length is an important parameter in the electron accelerator. The natural bunch length is generally defined as an rms value of a Gaussian bunch at zero beam current, but it varies as the beam current increases. The bunch length of the storage ring is usually on the order of ps. Direct measurement of the bunches of electrons is very difficult. Different techniques for bunch length measurement can be divided into time domain methods and frequency domain methods [1]. The absolute bunch length can be precisely obtained by streak camera in the time domain [2].

The frequency spectrum of a bunch contains all the information about the bunch shape and length. So far, Similar work has been done in several storage rings [3, 4] and two-frequency method has been used to measure the bunch length at SSRF [5]. In this paper, a multi-frequency harmonic analysis method based on the BPM (Beam Position Monitor) in the frequency domain is discussed. We use the BPM's button pickups as the electrodes. The signal passes through four BPFs (Band Pass Filters) with different center frequency to extract four operating points of the beam signal. Signals will be tuned and optimized by the integrated RF conditioning module. The bunch length information will be obtained by calibration with a streak camera.

PRINCIPLES

Suppose that ***f(t)*** is a Gaussian-shaped bunch containing ***N*** particles of charge ***e*** in a bunch of rms temporal length $\boldsymbol{\sigma}$ (in time units). Its frequency spectrum is given by the Fourier transform

$$F(\omega)=\int_{-\infty}^{+\infty} f(t)e^{-j\omega t}dt = eN\cdot\exp(-\frac{\sigma^2\omega^2}{2}). \quad (1)$$

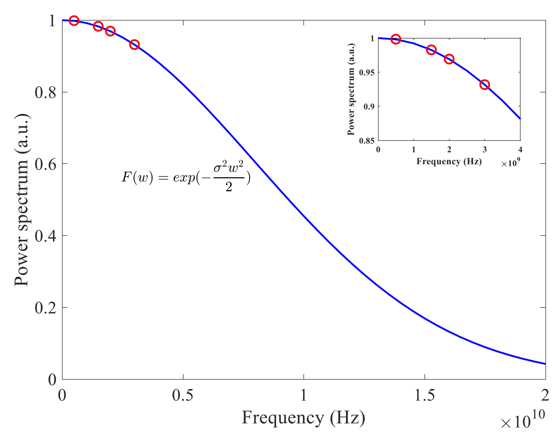

Figure 1: Power spectrum for Gaussian bunches.

In Fig. 1, if we get multi-frequency harmonic signals, the bunch length can be fit out by Gaussian in Eq.1. However, due to the difference in the transfer function between different channels and the limited bandwidth of the channel, a coefficient will be introduced in the formula for correction. Then the formula converts to:

$$F(\omega)=KQ\cdot\exp(-\frac{\sigma^2\omega^2}{2}). \quad (2)$$

How do we get the coefficient (***K***)? The bunch-by-bunch charge can be obtained by BPM sum signal, as shown in Fig.2. In the single-bunch mode, we have calibrated the relationship between beam length and charge with a streak camera, see Ref [6]. Since the bunch charge is less than 1nC, they are satisfied with a second-order Polynomial equation. Therefore, according to the equation, the absolute

*Work supported by National Natural Science Foundati on of China (No.11575282) and Ten Thousand Talent Program and Chinese Academy of Sciences Key Technology Talent Program
†zhouyimei@sinap.ac.cn
#lengyongbin@sinap.ac.cn

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bunch length corresponding to the bunch charge can be calculated.

In the multi-frequency bunch-by-bunch length measurement system, the amplitude value of each channel has been achieved, which can be considered as ***F(ω)***. Then, each K_i of different channels can be obtained through Eq.2.

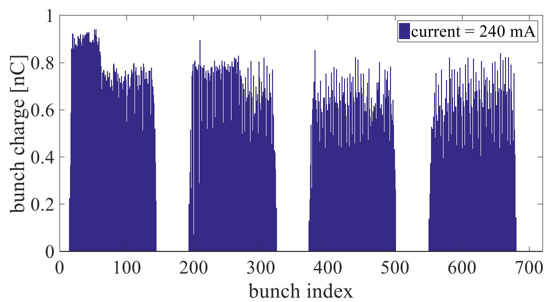

Figure 2: Bunch charge distribution under Top-off mode.

With the system response coefficients of different channels, we can accurately get the corresponding four frequency points in the spectrum. Then, the bunch length can be obtained by Gaussian fitting. The advantages of this method are:

1. Electrical signal extracted from BPM is simpler and more accurate than the optical signal;
2. The bunch length measurement can be directly performed in the user operation mode without changing the operating state of the machine;
3. It can directly perform multi-turn bunch-by-bunch length measurement with higher efficiency;
4. Relative to the streak camera, the price is cheaper.

SYSTEM SETUPS

The multi-frequency bunch-by-bunch length measurement system is mainly composed of the button BPM, an integrated RF conditioning module and a high-precision digitizer. Time delays between channels are strictly correction by the phase shifters. The system framework is shown in Fig.3. A 1.2GHz bandwidth digitizer (SP ADQ14) is used to acquire signals synchronously with a sampling rate of 1Gsps. The clock signal comes from the timing system, which is connected to a phase shifter to catch the wave maximum value. Four different frequency signals are achieved after processing and conditioning by an integrated RF front end. Four phase shifters are connected to the output to ensure that the four channels of the system have the same phase. The detail block diagram of the RF conditioning module is shown in Fig.4.

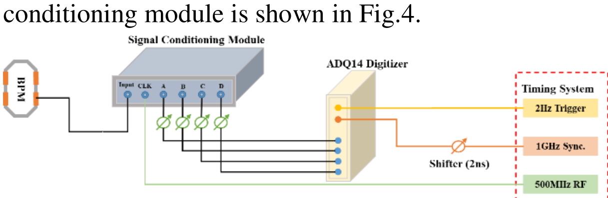

Figure 3: Framework of the multi-frequency bunch-by-bunch length measurement system.

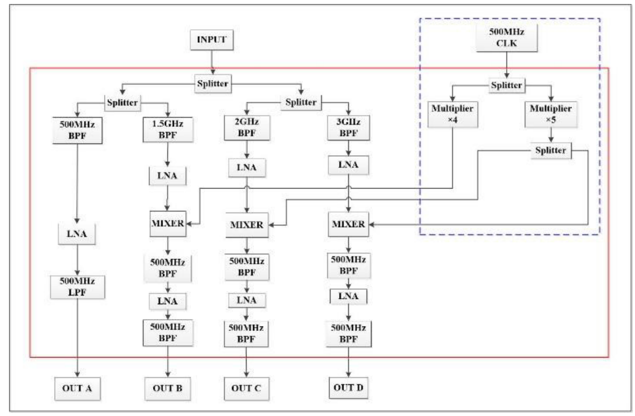

Figure 4: Block diagram of the RF conditioning module.

The signal from one button BPM is divided into four channels by three two-way power splitters with the bandwidth of 10-3700MHz. One channel passes through a 500MHz band-pass filter and is amplified and filtered to become the basic signal in the bunch length measurement. The remaining three channels are mixed with the local oscillator (LO) signal from the time module after passing through the 1.5 GHz, 2 GHz and 3 GHz band-pass filters. The purpose is to down-convert the signals to 500MHz. This method extracts the 3rd harmonic, 4th harmonic and 6th harmonic of the BPM signal as the operating frequency points.

The band-pass filters are very significant components of our measurement system. Figure 5 shows the S-parameter of three BPFs. The center frequency is 1.5GHz, 2GHz, 3GHz, and all of the bandwidth is about 600MHz. In addition to the required frequency, the sup-press of the remaining harmonic frequencies reaches 40dB.

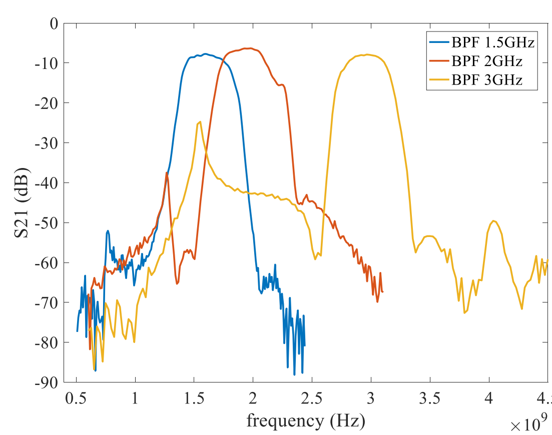

Figure 5: S-parameter of the 1.5GHz, 2GHz, 3GHz filters.

The LO signal of the mixer is provided by the time module, which must be phase locked to the machine RF signal. Multipliers with 4x and 5x frequency are used to generate the 2GHz and 2.5GHz local oscillator signals.

Finally, the high-frequency harmonic signals are amplified and output after 500MHz bandpass filtering, while the 500MHz basic signal is filtered by a low pass filter, preserving the low frequency.

DATA ANALYSIS

Experimental Raw Data Analysis

Bunch-by-bunch length measurement experiment is performed under the user operation mode. The total beam current is 240mA. The signals acquired by the ADQ digitizer are shown in Fig.6 and the frequency spectrums of them are shown in Fig.7. From the results, there is a very obvious interference signal in the 2GHz channel, and its source is still unclear. It will be removed in the next step. From the frequency domain, the noise of the three channels is significantly higher than the 500MHz signal. Furthermore, there is a significant transverse tune in the spectrum, which introduces errors in the measurement of the longitudinal bunch length.

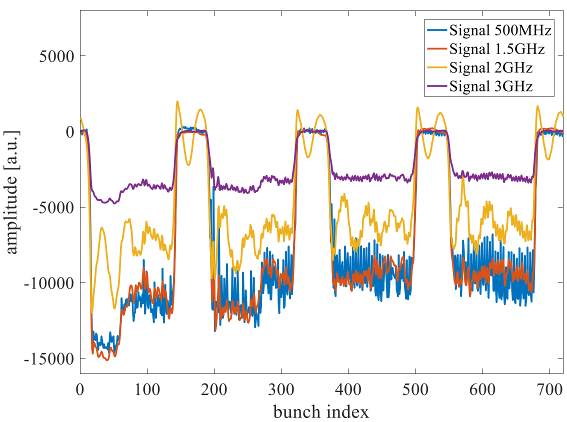

Figure 6: Experimental raw signals of the bunch-by-bunch length system.

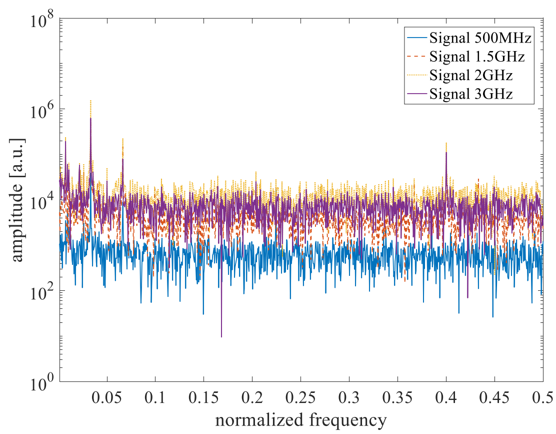

Figure 7: Frequency spectrum of the raw signals.

Error Analysis

In theory, the actual measured values ($\frac{F(\omega_i)}{K_i Q}$) of the four operating frequency points can be obtained according to the calibrated $\boldsymbol{K_i}$. Then, bunch length is fitted out by Gaussian. However, in terms of theoretical error, the amplitude error is 0.2% at 500MHz, 1.8% at 1.5GHz, 3.2% at 2GHz and 7% at 3GHz. But for our system, the measurement error of each channel is shown in Figure 8. The maximum RMS of the amplitude at 3GHz has reached 15%, which has far exceeded the theoretical Gaussian fitting error. Therefore, the fitting result is not ideal in the beam length measurement. We will continue to improve the system and ultimately achieve bunch-by-bunch length measurement. The system will be applied to a six-dimensional bunch-by-bunch synchronous diagnostic system at SSRF.

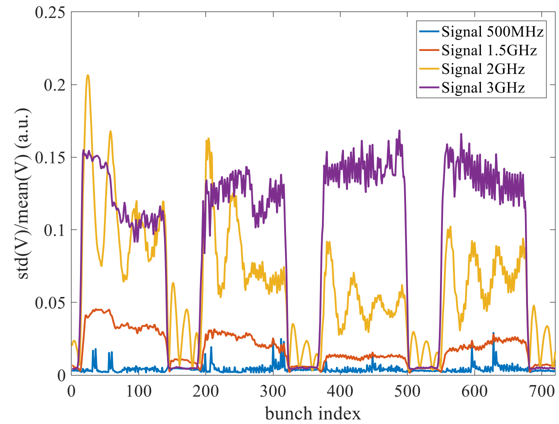

Figure 8: Error of the bunch-by-bunch length system.

CONCLUSIONS

A multi-frequency bunch-by-bunch length measurement system with integrated RF conditioning module is successfully implemented at SSRF. Experimental testing and error analysis have been completed. Although some problems were brought about in the bunch length measurement, the feasibility of the experimental scheme was verified. In the next step, we will work to reduce system noise and increase measurement resolution. Furthermore, the system will be used for the 6-dimensional bunch-by-bunch diagnostic system at SSRF.

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