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Injection transient study using a two-frequency bunch length measurement system at the SSRF

Li-Wu Duan[1] · Yong-Bin Leng[1,2] · Ren-Xian Yuan[1,2] · Zhi-Chu Chen[1,2]

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Abstract The bunch length can be measured by comparison of two frequency components of a synchrotron beam signal. An online bunch length measurement system has been implemented based on this method. Working frequencies of 3 GHz and 500 MHz were selected, and the raw data was acquired by digital oscilloscope and was resampled and analyzed using the MATLAB software platform at bunch-by-bunch rate. The constructed system was employed to study the bunch length synchronous oscillation phenomenon during injection. The beam experiments demonstrated a time resolution of less than 0.5 ps.

Keywords Bunch length measurement · Two-frequency method · Bunch-by-bunch · Injection

1 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. To produce high brilliance pulses, bunch length and beam emittance should be regulated within appropriate ranges. Moreover, the bunch length is an important factor of the overall beam performance.

Bunch length was previously measured at the SSRF using a streak camera [1]. Bunch-by-bunch measurements can be obtained, and a resolution of 2 ps can be achieved using this method. However, the performance of this method requires complicated optical structures and continuous operator monitoring to address operational contingencies. Moreover, the measurement mechanism involved makes it difficult to follow dynamical changes in the bunch length [1–7]. Thus, a real-time measurement or analysis method is required at the SSRF for daily operation.

The two-frequency method provides a means of indirectly measuring the bunch length in the frequency domain. Average bunch length measurements by this method at CERN have provided a resolution of about 0.7 ps [8]. The two-frequency method employs an electronic system that can provide online bunch-by-bunch measurements and be integrated into the EPICS control network if configured with the development of the beam diagnostics technique at the SSRF.

A two-frequency measurement system is comprised of radio frequency (RF) front-end electronics, a real-time data acquisition module, and a high-level data analysis package. Working frequencies of 3 GHz and 500 MHz were selected, and the RF front end was designed and constructed on the basis of these two frequencies. A high-sampling-rate multi-channel oscilloscope served as a convenient data acquisition device, and the raw data was resampled and analyzed using the MATLAB software platform. The constructed system was employed to study the bunch length synchronous oscillation phenomenon during injection, and further beam experiments confirm the relationship between bunch length and bunch charge.

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✉ Yong-Bin Leng
lengyongbin@sinap.ac.cn

1 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

2 Shanghai Synchrotron Radiation Facility, Chinese Academy of Sciences, Zhangjiang Campus, Shanghai 201204, China

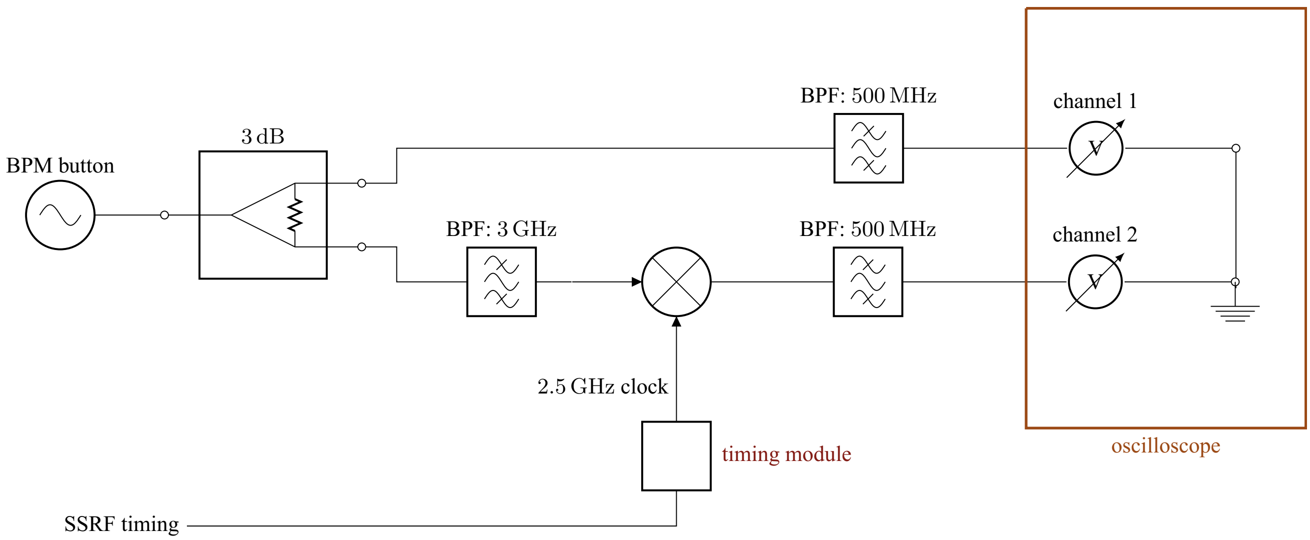

Fig. 1 (Color online) Block diagram of the bunch length measurement system

2 Principles and analysis

The longitudinal charge distribution of an electron bunch in a storage ring is typically Gaussian, and the Fourier component of the m_i-th harmonic is given as

$$V(m_i\omega_0) = 2V_0 \exp\left(-\frac{m_i^2\omega_0^2\sigma^2}{2}\right), \tag{1}$$

where ω_0 is the RF frequency 499.68 MHz employed at the SSRF, and V_0 is the DC component. In the two-frequency method, the bunch length, σ, is obtained as the ratio between two Fourier components as follows [8–19]:

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

Here, V_1 and V_2 are the actual measured value of the m_1-th and m_2-th harmonics, where the m_2 is greater than m_1, and K is a coefficient that depends on the two frequencies.

When a bunch runs across from the electrical center of beam-position monitor (BPM), there is an influence by transverse deviation, but it can be dispelled. The response coefficients of the pickup and analog front end vary at different frequencies, and both contribute to the value of K. However, K is a constant for the two specified frequencies on a fixed system.

For independent V_1 and V_2, the uncertainty of the bunch length is propagated from the two signals:

$$\begin{aligned}\left(\frac{\Delta\sigma}{\sigma}\right)^2 &\simeq \frac{1}{4\ln^2\left(\frac{KV_1}{V_2}\right)}\left[\left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta V_2}{V_2}\right)^2\right] \\ &= \frac{1}{\left(m_1^2 - m_2^2\right)^2\omega_0^4\sigma^4}\left[\left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta V_2}{V_2}\right)^2\right],\end{aligned} \tag{3}$$

where $\Delta V_1, \Delta V_2$, and $\Delta\sigma$ are the resolutions of the output signals V_1 and V_2, and the error propagation, respectively. In most occasions, the signal-to-noise ratios (SNR) of V_1 and V_2 are close enough that $SNR(V_1) = SNR(V_2) = SNR(V)$ stands. In that case, the relative resolution of the calculated bunch length can be estimated:

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{2}}{\left|m_1^2 - m_2^2\right|\omega_0^2\sigma^2}\frac{1}{\mathrm{SNR}(V)}. \tag{4}$$

The resolution will suffer a severe enlargement during the calculation when $|m_1^2 - m_2^2| \ll \frac{1}{\omega_0^2\sigma^2}$, i.e., the two frequencies are too close.

3 Measurement system setup

A block diagram of the bunch length measurement system including RF front-end electronics, timing module, and a digital oscilloscope is shown in Fig. 1.

The beam signal derived from a button-type pickup is divided into two channels by a two-way zero-degree power splitter. Each channel incorporates a corresponding band-pass filter with center frequencies of 500 MHz or 3 GHz to obtain signals at the working frequencies. The timing module produces a 2.5-GHz clock signal serving as a local oscillator (LO) employed in conjunction with a mixer to output an intermediate frequency of 500 MHz from the filtered 3 GHz signal. The digital oscilloscope then acquires data from both channels after the adjusted channel signal has passed through another 500 MHz band-pass filter. Figure 2 presents a photograph of the RF front end employed in the measurements.

The 500 MHz band-pass filter was a very significant component of our measurement system.

Figure 3 presents an *S*-parameter chart of the WI Corp. 500 MHz band-pass filter obtained by the network analyzer in laboratory. The filter bandwidth is 350 to 650 MHz, which can ensure the bandwidth required for bunch-by-bunch measurement. Moreover, the *S*-parameter chart indicates that transmission outside of the band is reduced from 40 to 50 dB, which reliably suppresses other high order harmonics.

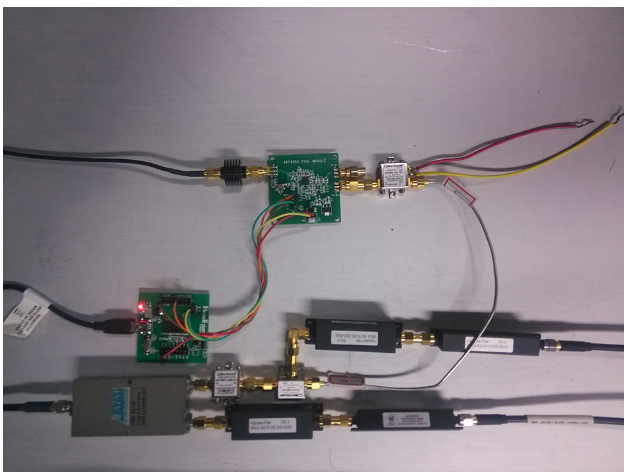

Fig. 2 (Color online) Photograph of the RF front-end electronics

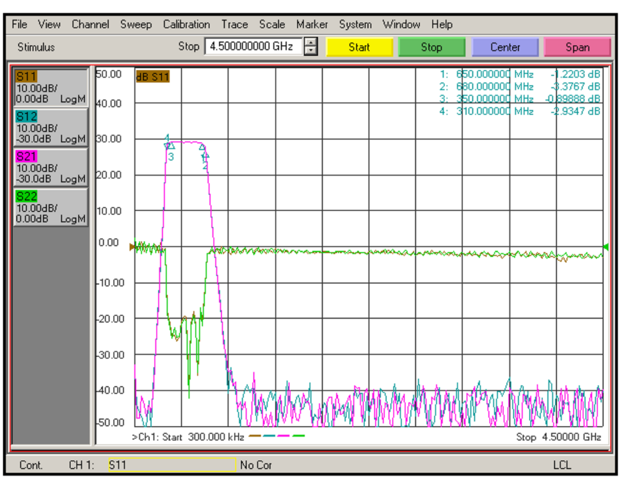

Fig. 3 (Color online) *S*-parameter chart of the 500 MHz filter employed in the measurement system

Real-time bunch-by-bunch measurement requires two frequency signals synchronized with the machine RF signal. Therefore the 2.5 GHz LO input signal of the mixer must be generated according to a timing signal that is phase locked to the machine RF signal. A programmable wide band frequency synthesizer, (EVAL-ADF4351, ADI Corp.), was employed to this. The EVAL-ADF4351 is a phase-locked loop (PLL) evaluation unit with an integrated voltage-controlled oscillator (VCO) whose input reference frequency is 250 MHz at maximum and with an output frequency range from 35 MHz to 4.4 GHz. In our application, the revolution frequency of 694 kHz from the timing system is employed as the input reference, and the multiplication factor of 3600 was configured to output a 2.4984 GHz signal. The amplitude response of this module is shown in Fig. 4, as measured using a Tektronix RSA6114A network analyzer.

The phase noise of the sideband is less than -27.1 dBc/Hz, which obviously cannot have a large impact on the intermediate frequency signals of the mixer because its power is insufficient to support mixing. Actual experiments reveal that different frequencies signals can be reliably locked.

A digital oscilloscope is adopted as a DAQ device due to its high dynamic range. However, the sampling rate of the raw data captured by the oscilloscope is 5 GHz, which is not synchronized with the machine RF signal. Therefore, a software resampling technique was required in the data analysis procedure [20]. The MATLAB software platform was employed to this purpose. The RF frequency obtained

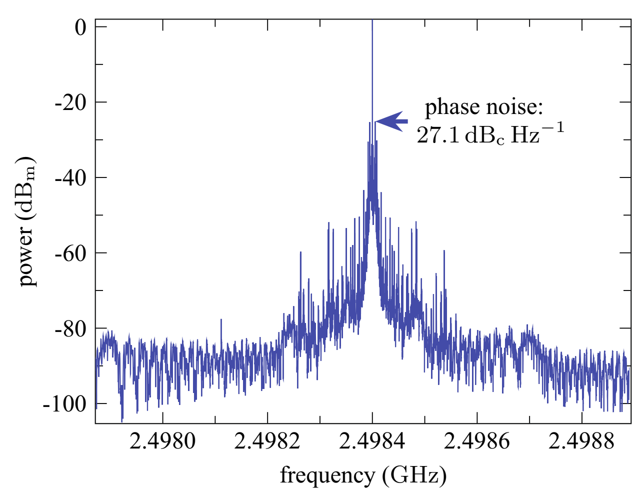

Fig. 4 (Color online) Amplitude response spectrum of EVAL-ADF4351 programmable wide band frequency synthesizer (ADI Corp.) employed in the measurement system

from the discrete Fourier transformation of the raw waveform was employed to determine the bunch interval. Cubic spline interpolation was used to obtain bunch-by-bunch length information at accurate signal phases. With the resampled amplitude information, the bunch charge and length can be calculated correctly at the bunch-by-bunch rate.

4 Beam experiments

Suitable beam experiments must be conducted to verify the functionality of the proposed bunch length measurement system. An ideal beam experiment involves adjusting the RF cavity voltage to change the bunch length and then compares the measured value with the expected value. However, the SSRF is a multiple-user facility, and this test is therefore impractical. Another suitable and performable choice is the observation of the beam injection transient, which is frequently observable in the top-up operation mode at the SSRF, where the bunch length of the refilled bunch varies considerably during injection.

4.1 Observation of beam injection transient

Bunch injection induces damping betatron oscillation due to the timing mismatch of kickers and damping synchronous oscillation due to the phase mismatch of refilled charge. Figure 5 presents a conceptual model of the effect of the injection transient.

The refilled bunch is a conjunction of the originally stored charge and the small, newly injected charge. After injection, the injected charge oscillates around the stored charge in the longitudinal plane, which creates a corresponding bunch length oscillation, the amplitude of which decreases gradually. The oscillation frequency is double that of the SSRF storage ring synchrotron frequency.

A practical beam experiment was conducted using a 240 mA beam on April 11, 2016. The relative bunch charge information was retrieved from the channel one (500 MHz)

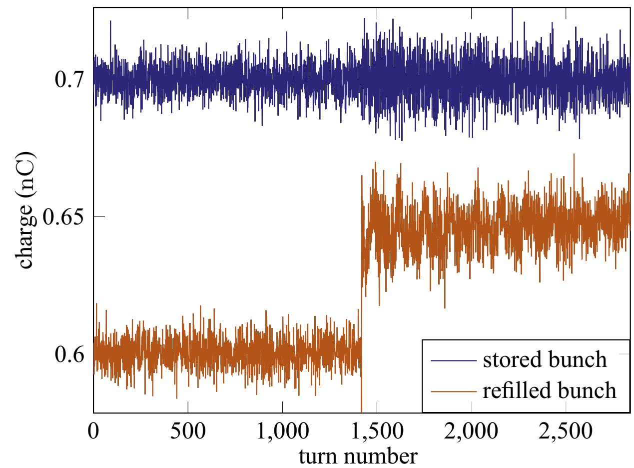

Fig. 6 (Color online) Variation in bunch charge during injecting

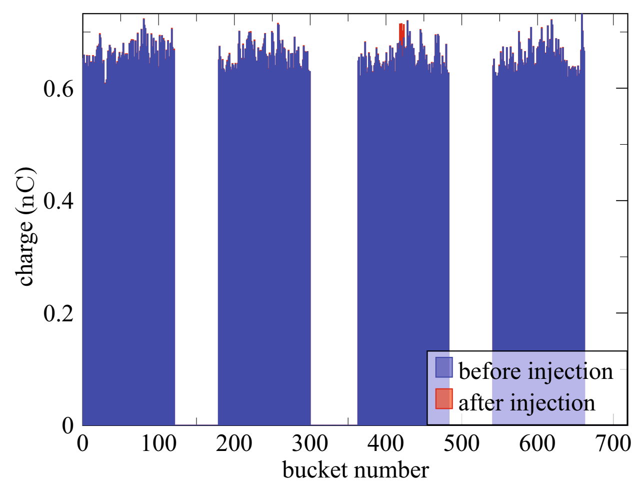

Fig. 7 (Color online) Bunch filling mode during injecting

data. The turn index of injection can be determined by comparing raw waveforms of the stored and refilled bunches, which is shown in Fig. 6.

With the correct injection turn index, the filling pattern before and after injection can be calculated, as shown in Fig. 7. Subtraction of the two patterns provides the refilled bunch indices, which are 419–425 in this case.

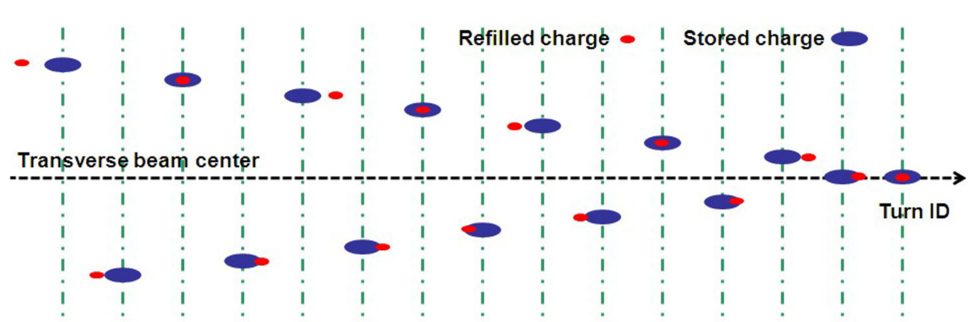

Fig. 5 (Color online) Synchronous oscillation and betatron oscillation during injecting

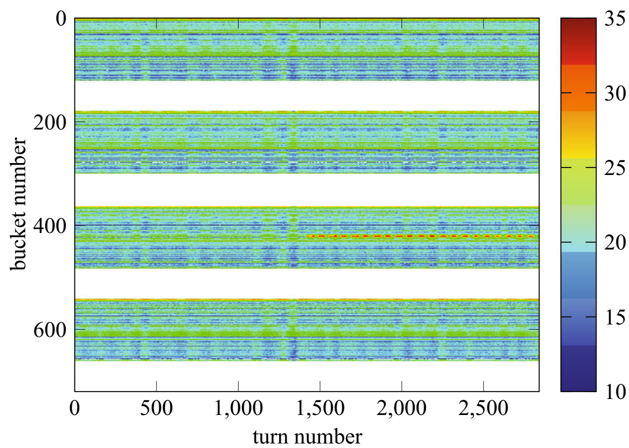

Fig. 8 (Color online) Waterfall plot of the measured bunch length at each bucket. The injected bunches can be noticed since their lengths oscillate up to 35 ps (the *dashed*, *dark red line* around the 400th row)

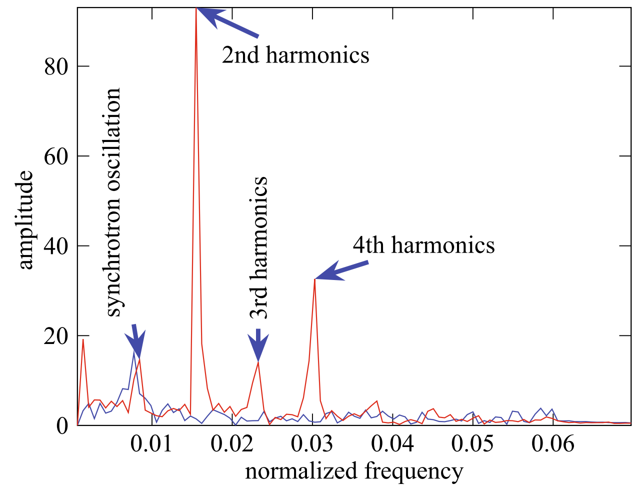

Fig. 10 (Color online) Spectra of the bunch lengths before and after the injection at the refilled bucket

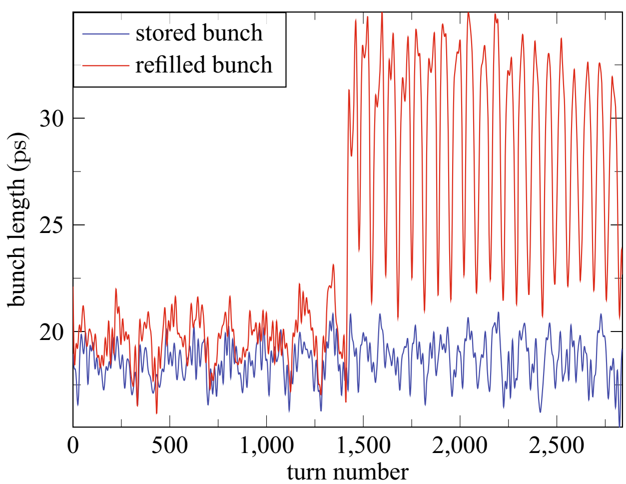

Fig. 9 (Color online) Synchronous oscillation of bunch length

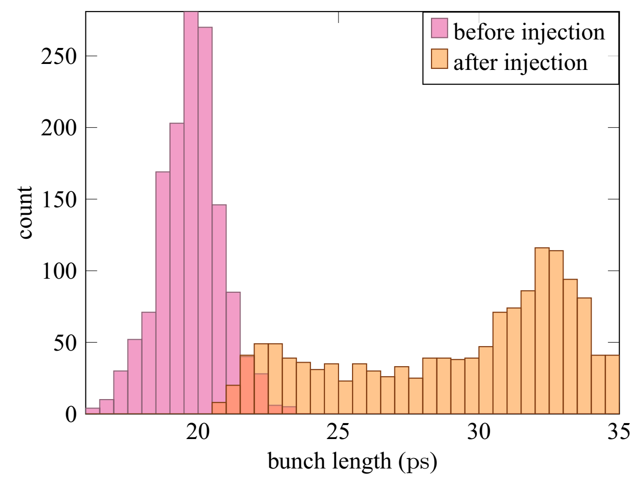

Fig. 11 (Color online) Histogram of the bunch lengths before and after the injection

Figure 8 presents a waterfall plot indicative of the measured bunch length. The bunch length oscillation of the refilled bunches (419–425, given by the light yellow dashed line in Fig. 8) can be observed as well.

Figure 9 presents a plot of the refilled bunch length as a function of the turn index, which clearly demonstrates the synchronous oscillation illustrated in Fig. 5 due to the merging of the stored charge and injected charge. As a reference, the stored bunch is plotted as well by the blue line, demonstrating a very stable bunch length over the period of the procedure. In this case, the accelerator phase of the injected charge is not matched with the synchronous phase of the stored charge, resulting in a gradually decreasing amplitude of oscillation, as shown by the red curve in the plot.

If we conduct a Fourier analysis of the refilled bunch oscillation and the stored bunch, we attain their frequency spectrum, as shown in Fig. 10. We find its highest peak resides at the second harmonics of the normalized frequency of 0.007 and the third and fourth harmonics are notable comparing with the stored bunch line, which matches the synchrotron frequency of the SSRF exactly. These results verify whether our bunch length measurement system was constructed correctly and operated successfully.

5 Measurement resolution

The standard deviation of the bunch length was 1.11 ps and it became 4.05 ps after the injection (as shown in Fig. 11).

According to Eqs. (3) or (4), the measurement resolution is restrained by the SNR. The SNR of the electronics was obtained by measuring the signals from the button with stored beams and without filling any bucket. Setting up an appropriate scale, the amplitudes of the signals with beams were around 120 mV, and the standard deviation of the noise is about 0.58 mV. Four data points near the peak were used to determine the output voltage of a bunch during the experiment, so the SNR gains a boost by a factor of 2. Applying $m_1\omega_0 = 2\pi \times 500$ MHz, $m_2\omega_0 = 2\pi \times 3$ GHz, $SNR(V) = 2 \times \frac{120}{0.58}$, and $\sigma = 20$ ps in Eq. (4), we can see that the resolution is 0.49 ps.

6 Conclusion

Bunch-by-bunch measurement of the bunch length is an important tool that can facilitate the daily monitoring of the SSRF storage ring and act as a supplement to streak camera absolute measurement of the bunch length.

The present work discussed the construction of an electronic system employing the two-frequency method that achieves bunch length measurements at the bunch-by-bunch rate. Bunch injection experiments accurately disclosed the phenomenon of bunch length synchronous oscillation, and the fusing process of the injected bunch and the stored one was observed for the first time. A time resolution of no more than 0.5 ps was demonstrated for the proposed design.

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References

1. J. Chen, R. Yuan, Z. Chen, et al., Bunch length measurement with streak camera at SSRF storage ring, in *Proceedings of IBIC2013* (Oxford, UK), pp. 478–480
2. J.C. Sheppard, J.E. Clendenin, M.B. James et al., Real time bunch length measurements in the SLC linac. IEEE Trans. Nucl. Sci. **32**, 2006–2008 (1985). doi:10.1109/TNS.1985.4333796
3. A.S. Fisher, R.W. Assmann, A.H. Lumpkin et al., Streak-camera measurements of the PEP-II high-energy ring, in *AIP Conference Proceedings*, vol. 451 (1998), pp. 471–478. doi:10.1063/1.57033
4. M. Uesaka, T. Ueda, T. Kozawa et al., Precise measurement of a subpicosecond electron single bunch by the femtosecond streak camera. Nucl. Instrum. Methods A **406**, 371–379 (1998). doi:10.1016/s0168-9002(97)01220-5
5. T. Watanabe, M. Uesaka, J. Sugahara et al., Subpicosecond electron single-beam diagnostics by a coherent transition radiation interferometer and a streak camera. Nucl. Instrum. Methods A **437**, 1–11 (1999). doi:10.1016/s0168-9002(99)00674-9
6. M. Geitz, G. Schmidt, P. Schmser et al., Sub-picosecond bunch length measurement at the TESLA test facility. Nucl. Instrum. Methods A **445**, 343–347 (2000). doi:10.1016/s0168-9002(00)00140-6
7. Z. Zhao, Z. Guo, D. Liu et al., The bunch length measurement of BEPC with a streak camera, in *Proceedings of the second Asia Particle Accelerator Conference* (Beijing, China, 2001), pp. 598–600
8. H.H. Braun, C. Martnez, Non-intercepting bunch length monitor for picosecond electron bunches, in *Proceedings of the 6th European Particle Accelerator Conference* (Stockholm, Sweden, 1998), pp. 1559–1561
9. T. Ieiri, High-resolution bunch-length monitor capable of measuring an rms value of a few mm. Nucl. Instrum. Methods A **361**, 430–435 (1995). doi:10.1109/pac.1997.751089
10. B. Gagliardo, A. Mostacci, D. Alesini et al., Electromagnetic simulations and RF measurements results of an ultra-short bunch length monitor, in *Proceedings of EPAC 2002* (Paris, France, 2002), pp. 1834–1836
11. T. Mimashi, H. Mizuno, N. Iida et al., Bunch length measurement and the beam signal observation through high power RF waveguide system, Technical Report, SLAC-PUB-10359. doi:10.2172/826787
12. F. Zimmermann, G. Yocky, D. Whittum et al., An RF bunch-length monitor for the SLC final focus, in *Proceedings of the Particle Accelerator Conference* vol. 2 (1997), pp. 2189–2191. doi:10.1109/pac.1997.751151
13. Z. Greenwald, D. L. Hartill, R. M. Littauer et al., Bunch length measurement using beam spectrum (CESR storage ring), in *Particle Accelerator Conference, 1991. Accelerator Science and Technology, Conference Record of the 1991 IEEE* (1991), pp. 1246–1248. doi:10.1109/pac.1997.751151
14. T.P.R. Linnecar, D. Stellfeld, "Measurement of lepton bunch length in the SPS", CERN-SL-RFS-Note-90-03 (1990)
15. Z. Guo, Q. Qin, G. Xu et al., Bunch lengthening study in BEPC, in *Proceedings of PAC95*, Dallas TX, (1995), pp. 2955–2957. doi:10.1109/pac.1995.505749
16. R. Kuroda, S. Kashiwagi, K. Sakaue et al., Bunch length monitor using two-frequency analysis for RF gun system. Jpn. J. Appl. Phys. **43**(11R), 7747 (2004). doi:10.1143/jjap.43.7747
17. T. Ieiri, in *Proceedings of EPAC 2000* (Vienna, Austria, 2000), pp. 1735–1737
18. Q. Qin, Z. Guo, G. Xu et al., Studies of bunch lengthening at the BEPC. Nucl. Instrum. Methods A **463**, 77–85 (2001). doi:10.1109/pac.1995.505749
19. T. Ieiri, A real time bunch length monitor in the TRISTAN AR, in *AIP Conference Proceedings*, vol. 229 (1991), pp. 280–286. doi:10.1063/1.40749
20. Y. Yang, Y. Leng, Y. Yan et al., Bunch-by-bunch beam position and charge monitor based on broadband scope in SSRF, in *Proceedings of 4th International Particle Accelerator Conference* (Shanghai, China, 2013), pp. 595–597