Bunch-length measurement at a bunch-by-bunch rate based on time-frequency-domain joint analysis techniques and its application

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Abstract

This paper presents a new technique for measuring the bunch length of a high-energy electron beam at a bunch-by-bunch rate in storage rings. This technique uses the time-frequency-domain joint analysis of the bunch signal to obtain bunch-by-bunch and turn-by-turn longitudinal parameters, such as bunch length and synchronous phase. The bunch signal is obtained using a button electrode with a bandwidth of several gigahertz. The data acquisition device was a high-speed digital oscilloscope with a sampling rate of more than 10 GS/s, and the single-shot sampling data buffer covered thousands of turns. The bunch length and synchronous phase information were extracted via offline calculations using Python scripts. The calibration coefficient of the system was determined using a commercial streak camera. Moreover, this technique was tested on two different storage rings and successfully captured various longitudinal transient processes during the harmonic cavity debugging process at the Shanghai Synchrotron Radiation Facility (SSRF), and longitudinal instabilities were observed during the single bunch accumulation process at Hefei Light Source (HLS). For Gaussian-distribution bunches, the uncertainty of the bunch phase obtained using this technique was better than 0.2 ps, and the bunch length uncertainty was better than 1 ps. The dynamic range exceeded 10 ms. This technology is a powerful and versatile beam diagnostic tool that can be conveniently deployed in high-energy electron storage rings.

Full Text

Preamble

This paper presents a novel technique for measuring the bunch length of high-energy electron beams at a bunch-by-bunch rate in storage rings. The method

employs time–frequency-domain joint analysis of bunch signals to obtain bunch-by-bunch and turn-by-turn longitudinal parameters, including bunch length and synchronous phase. Bunch signals are acquired using a button electrode with several gigahertz bandwidth. Data acquisition is performed with a high-speed digital oscilloscope operating at over 10 GS/s, with a single-shot sampling buffer covering thousands of turns. Bunch length and synchronous phase information are extracted through offline calculations using Python scripts. The system calibration coefficient is determined using a commercial streak camera. This technique was validated on two different storage rings, successfully capturing various longitudinal transient processes during harmonic cavity commissioning at the Shanghai Synchrotron Radiation Facility (SSRF) and observing longitudinal instabilities during single-bunch accumulation at the Hefei Light Source (HLS). For Gaussian-distributed bunches, the phase uncertainty achieved with this technique is better than 0.2 ps, and the bunch length uncertainty is better than 1 ps, with a dynamic range exceeding 10 ms. This technology serves as a powerful and versatile beam diagnostic tool that can be conveniently deployed in high-energy electron storage rings.

Keywords: bunch-by-bunch diagnostic, bunch-length measurement, synchronous phase measurement, joint time–frequency domain analysis, longitudinal instability

INTRODUCTION

Advances in accelerator technology over recent decades have led to reduced beam sizes and emittances, necessitating the development of advanced beam diagnostic techniques. Bunch length, a fundamental parameter in accelerator systems, is critical for determining brightness and emittance. Consequently, accurate bunch-length measurements are essential for ensuring stable accelerator operation.

Several methods have been developed for bunch-length measurements, including streak cameras, transverse deflecting cavities [?, ?], electro-optical sampling, autocorrelators, cross-correlators [?, ?], and spectral analysis. Streak cameras are widely used in facilities such as NSLS-II [?], SSRF [?], PEP-II [?], ANKA [?, ?], and BESSY II [?]. Streak cameras provide precise measurements of longitudinal bunch length and spatial distribution of individual bunches without beam impact. When the dynamic range is sufficiently small, detailed phenomena such as filamentation of freshly injected bunches in real space can be observed on a picosecond scale [?]. However, streak cameras are limited by their finite pixel resolution, making it challenging to simultaneously achieve extensive dynamic range and high time resolution.

A typical example is the measurement of injected bunch damping times at ALBA in 2012. The measurement required the streak camera to cover the entire injection process, which limited the time resolution and prevented turn-by-turn evolution studies [?, ?]. In 2018, the ALBA group focused on longitudinal oscillation amplitudes and frequencies, requiring high time resolution to observe bunch waveforms. However, the streak camera’ s dynamic range could not cover the entire damping oscillation process, preventing accurate determination of the damping time.

In 2016, BINP SB RAS developed a dissector measurement technique similar to streak cameras [?]. The dissector converts optical signals to electrical signals for measurement with photomultiplier tubes. The Metrology Light Source (MLS) used a dissector for bunch-length measurements in combination with a streak camera [?]. However, dissectors lack universality and high resolution, and cannot fully replace streak cameras.

Although electro-optical sampling is commonly used in linear accelerators, efforts have been made to apply it to storage rings. For example, the KIT storage ring KARA performed longitudinal single-shot optical detection of electron bunches, obtaining valuable long-timescale measurements [?]. Subsequent analysis examined beam charge density distribution and dynamic beam profile properties [?], and the complete spectral information of coherent synchrotron radiation was obtained [?]. However, electro-optical sampling has seen limited application as a general diagnostic technique for storage rings.

In bunch spectrum analysis, the dual-frequency method has demonstrated relatively high measurement accuracy, with significant progress made at institutions such as KEKB [?, ?] and ANKA [?]. However, traditional dual-frequency systems have narrow bandwidths and can only provide average bunch lengths for multiple bunches over many turns. In 2014, SSRF explored a dual-frequency-based bunch-by-bunch measurement technique [?, ?], but limited signal-to-noise ratio and significant inter-bunch crosstalk prevented the measurement accuracy from meeting most machine study requirements. In another development, PLS-II used fast photodiodes to detect synchrotron light signals and analyzed the spectral structure to calculate bunch length [?]. However, signal processing limitations prevented bunch-by-bunch and turn-by-turn measurements, and insufficient probe bandwidth prevented accurate measurement of sub-20-ps bunches.

Since 2012, the SSRF beam instrumentation group has developed a multiparameter diagnostic method for electron storage rings based on broadband random sampling technology. This method uses button-electrode signals and visible synchrotron radiation as sources, high-speed digital oscilloscopes for data acquisition, and offline software for oscilloscope data analysis. The system accurately measures parameters such as charge, transverse position [?, ?], bunch length, longitudinal phase [?], and transverse bunch size [?]. Building upon this foundation, an open-source software package called HOTCAP [?] was developed to enable simultaneous three-dimensional position and charge measurement [?], applicable to any high-energy electron storage ring. Numerous application studies have been conducted using this tool, including evaluation of injection dynamics [?], analysis of transverse wakefields [?], observation of longitudinal damping oscillations of refilled bunches [?], in-situ diagnosis of optical parameters [?], and assessment of beam loading effects in harmonic cavities.

The remainder of this paper is organized as follows: Section II presents the theoretical basis for bunch length calculation; Section III describes the experimental setup, including the platform, measurement system, bunch length calculation process, and uncertainty evaluation; Section IV presents beam experiments and results from HLS and SSRF; Section V discusses the results; and Section VI provides conclusions.

II. THEORETICAL BASIS

A. Determinants of Bunch Length

The bunch length in a storage ring can be determined using electron-optical machine parameters. If the beam energy spread follows a Gaussian distribution, the root mean square (RMS) bunch length can be expressed as:

$$\sigma_{\Delta s} = \frac{p_0 \beta_0 \eta_c}{2\pi f_0} \sqrt{\frac{\sigma_p}{eV\cos(\phi_s)}}$$

where σ_p is the relative momentum spread, p_0 is the equilibrium particle momentum, η_c is the momentum compaction factor, f_0 is the particle revolution frequency, V is the equivalent longitudinal electric field (RF field, harmonic cavity field, and wakefield), and ϕ_s is the synchronous phase. The longitudinal bunch distribution is determined by the equivalent longitudinal electric field, energy spread, acceleration phase, and momentum compaction factor. Bunch length is a crucial beam parameter that reflects whether the electron storage ring meets design specifications or operates in a good condition. Accurate bunch length measurement is essential for stable accelerator operation and acceptance testing of newly constructed facilities.

In storage rings, bunch length variations arise primarily from changes in the effective longitudinal electric field V and acceleration phase ϕ_s. For example, longitudinal dipole oscillations can occur during longitudinal instabilities, resulting in changes in ϕ_s. When fresh bunches are injected, the initial phase deviates from equilibrium. Changes in V and ϕ_s can also result from RF system tuning or transient beam wakefield effects. Precise quantitative analysis of these phenomena can be achieved by capturing and measuring bunch length evolution on a turn-by-turn basis, providing a powerful tool for nonlinear beam dynamics research. Therefore, accurate diagnosis and measurement of bunch length on a bunch-by-bunch and turn-by-turn basis are crucial for storage rings.

Assuming the bunch length depends only on V and ϕ_s, Eq. (1) can be written as:

$$\sigma_{\Delta s}(V, \phi_s) = \frac{a}{\sqrt{V\cos(\phi_s)}}$$

where $a = \frac{p_0\beta_0\eta_c}{2\pi f_0}\sqrt{\frac{\sigma_p}{e}}$ is a constant for each machine. Taking the partial derivatives of Eq. (2), we obtain:

$$\frac{\partial\sigma_{\Delta s}(V,\phi_s)}{\partial V} = -\frac{a}{2V^{3/2}\sqrt{\cos(\phi_s)}}$$

$$\frac{\partial\sigma_{\Delta s}(V,\phi_s)}{\partial \phi_s} = \frac{a\tan(\phi_s)}{2\sqrt{V}\cos^{3/2}(\phi_s)}$$

Thus, when the RF cavity voltage and bunch phase change within a small range, the change in bunch length $\Delta\sigma$ is linearly related to the changes in cavity voltage ΔV and phase $\Delta\phi_s$.

B. Bunch-Length Measurement Principle

For an ideal Gaussian distribution, the beam signal in the time domain is given by:

$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(t-t_0)^2}{2\sigma^2}\right)$$

where Q denotes the bunch charge, σ is the bunch length, and t_0 is the bunch phase. The principle of beam signal acquisition in a storage ring is illustrated in Fig. 1 [Figure 1: see original paper]a and Fig. 1b.

When the beam passes through the button electrode, the detected signal can be expressed as:

$$V_b(t) = \frac{dI(t)}{dt}\cdot\frac{ab}{4\pi\varepsilon_0 c}\cdot F(\delta,\theta)\cdot Z_0$$

where a and b represent the physical dimensions of the button electrode, $F(\delta,\theta)$ represents the transverse position of the bunch, and Z_0 represents the transfer impedance of the button electrode. The beam distribution and detected signal are shown in Fig. 1c, exhibiting Gaussian distribution and bipolar pulse characteristics, respectively.

In the time domain, the detected signal (voltage) can be expressed as the convolution of the beam signal (current) and the detection system impulse response:

$$V_b(t) = I(t) * H_{\text{Button}}$$

where H_{Button} is the time-domain response function. In the frequency domain, we have:

$$V(f) = I(f) \cdot R_{\text{Button}}(f) = Q \cdot \exp\left(-\frac{(2\pi f \sigma)^2}{2}\right) \cdot R_{\text{Button}}(f)$$

where $V(f)$ is the frequency-domain distribution of the detected signal, $I(f)$ is the frequency-domain distribution of the beam signal (Gaussian), $R_{\text{Button}}(f)$ is the frequency-domain transfer impedance, and σ_f is the reciprocal of the time-domain bunch length. Therefore, by measuring σ_f, the bunch length can be determined.

III. EXPERIMENTAL MEASUREMENT SYSTEM SETUP

A. Experimental Platform

Beam experiments were conducted at HLS and SSRF. The key parameters of the two facilities are listed in Table 1 .

B. Measurement System Structure

The structure of the bunch-by-bunch measurement system is illustrated in Fig. 2 [Figure 2: see original paper]. First, four-electrode signals from BPM probes were acquired using a high-sampling-rate, high-bandwidth digital oscilloscope. The signals were imported into a Python script for further analysis. In the three-dimensional bunch position calculation module of the script, the four-channel data were concatenated to form a bunch-by-bunch beam signal. The response function was reconstructed, and the longitudinal center position (phase) information of the bunch was extracted in the time domain using the response function vector projection method. The reconstructed response function was resampled to obtain the signal amplitude for each bunch. The transverse position and charge information of the bunch were obtained by applying difference and ratio algorithms.

C. Bunch-Length Calculation Process

The bunch-length calculation module calibrates the transfer impedance of the measurement system, as shown in Fig. 3e [Figure 3: see original paper]. The original continuous sampling data were sliced bunch-by-bunch and turn-by-turn. Single-bunch, single-turn data were subjected to spectral analysis after baseline subtraction. A streak camera was used to measure the bunch length and calculate the expected signal spectrum distribution. The measured signal spectrum (voltage spectrum) was divided by the expected signal spectrum (current spectrum) to obtain the system transfer function (impedance). Assuming the storage ring machine parameters remain constant, the system transfer impedance is a known quantity and does not require recalibration during subsequent data acquisition and processing. For bunch-length calculation, all measurement data were sliced and harmonically analyzed, and the background was subtracted to obtain the voltage signal spectrum. Dividing the voltage signal spectrum by the system transfer function yields the current signal spectrum. Gaussian fitting was performed on this spectrum to determine the bunch-length measurement results for each bunch and turn. Fig. 3f–Fig. 3i demonstrate data processing for different charges of 0.18 nC, 1.16 nC, and 2.39 nC, showing distinct differences in spectrum distribution. Gaussian fitting of the spectra enables determination of bunch lengths as 65 ps, 83 ps, and 88 ps, respectively.

D. Uncertainty Evaluation

At HLS, where significant longitudinal instability occurs, the uncertainty of the bunch-length measurement system was evaluated in single-bunch mode. By progressively increasing the charge of a single bunch and using principal component analysis (PCA) to separate bunch oscillation modes during longitudinal instability, the residual measurement data were calculated as the system measurement uncertainty (Fig. 4a [Figure 4: see original paper]).

At SSRF, where no apparent longitudinal instability exists in normal operation mode, the random errors of the measurement system were evaluated in multi-bunch operation mode. Assuming constant bunch length for each bunch, the standard deviation of bunch-length measurements over multiple turns for each bunch was calculated as the system measurement uncertainty. The dependence of bunch-length measurement uncertainty on bunch charges was analyzed for 500 bunches (Fig. 4b [Figure 4: see original paper]). Both experiments show that bunch-length measurement uncertainty is inversely proportional to bunch charge, consistent with expectations.

IV. BEAM EXPERIMENT AND RESULTS

To validate the performance of the new system, we measured bunch length under different charge conditions for a single bunch at HLS and observed longitudinal instability in the storage ring' s normal operating state. We also measured the dependence of bunch length on bunch charge at SSRF, investigated variations in bunch length with total beam current during harmonic cavity tuning, and captured and analyzed random events related to coherent beam instability.

A. Experiment at HLS

In the single-bunch experiment at HLS, the bunch charge was varied from 0.2 nC to 2.6 nC. Bunch length was measured synchronously using both a streak camera and the high-speed oscilloscope time-frequency analysis system. The average bunch lengths obtained from both methods show excellent agreement, as shown in Fig. 5a [Figure 5: see original paper]. Bunch length variation with different bunch currents results from longitudinal broadband impedance, formulated as [**?**]:

$$\sigma_t = \sigma_{t0}\left(1 + \frac{\alpha I_0}{2\nu_s^2 E/e}\left(\frac{\sigma_t}{t_0}\right)_{\text{eff}}\right)^{1/3}$$

where α is the momentum compaction factor, $\nu_s = \omega_s/\omega_0$ is the synchrotron tune, and σ_{t0} is the bunch length at zero intensity. The longitudinal broadband impedance of HLS was calculated to be 7.1 Ω.

In addition to providing average bunch length, the time-frequency analysis system captured bunch length evolution on a turn-by-turn basis. As shown in Fig. 5b [Figure 5: see original paper], the bunch length remained constant when the bunch charge was relatively low (0.18 nC). However, significant longitudinal instability occurred for bunch charges above a certain threshold, resulting in periodic oscillations in bunch length. Harmonic analysis of the turn-by-turn bunch length variations (Fig. 5c [Figure 5: see original paper]) revealed that the oscillation frequency decreased as bunch charge increased. Similarly, harmonic analysis of turn-by-turn phase variations (Fig. 5d [Figure 5: see original paper]) shows oscillation modes completely synchronized with bunch-length oscillations.

Owing to the use of a room-temperature copper cavity as the main RF cavity at HLS, higher-order mode (HOM) issues are quite severe. Additionally, numerous discontinuous beamline components in the storage ring, such as stripline beam position monitors (SBPM), beam scrubbing electrodes, and vacuum insertions, result in relatively high impedance and increase the likelihood of longitudinal instabilities. To investigate this, a typical dataset was recorded using the measurement system in normal operation mode at HLS (total current of 400 mA with 35 continuously filled bunches). Fig. 6a–Fig. 6c [Figure 6: see original paper] show the longitudinal center position and bunch length of the head, middle, and tail bunches, respectively, as functions of time. Fig. 6d–Fig. 6f [Figure 6: see original paper] present the corresponding reconstructed distributions. Both oscillations in bunch center positions and bunch lengths are significant, with frequencies in agreement as expected. Additionally, oscillation amplitudes were larger at the head and tail of the bunch train than in the middle.

B. Experiment at SSRF

At SSRF, the charge of a single bunch was gradually increased from 2 nC to 9.5 nC. The variation in bunch length with respect to bunch charge was measured using the time-frequency analysis system with an oscilloscope, as shown in Fig. 7a [Figure 7: see original paper]. The bunch length exhibited localized nearly linear increases with bunch charge. The longitudinal broadband impedance was calculated as 0.3 Ω, which is in good agreement with the design value [?].

During harmonic cavity tuning, the average bunch length was measured as a function of total beam current. Measurements were conducted in top-up mode with regularly spaced four-bunch trains, each containing 125 bunches. The total beam current was varied from 80 mA to 180 mA. The results are shown in Fig.

7b [Figure 7: see original paper] (marked by red diamonds), with a comparison provided for the case where the harmonic cavity was set to the non-working state, showing variation in average bunch length with beam current (marked by blue circles). The comparison clearly demonstrates that the harmonic cavity exhibited a bunch stretching effect, though the stretching factor was significantly smaller than the design target, indicating room for optimization.

The process continued by decreasing the detuning frequency of the harmonic cavity and increasing the total beam current to 200 mA. Owing to beam-loading effects, variations occurred in both bunch phase and bunch length at different positions within the bunch train. The results are presented in Fig. 7d [Figure 7: see original paper] and are consistent with simulation results for CEPC [**?**]. The difference in bunch length between the head and tail of the bunch train, which was less than 1 ps, was distinguishable. Additionally, a negative correlation was observed between bunch length and phase within the bunch train. Assuming an uncertainty of 1 ps for turn-by-turn measurements, the random error after averaging 7000 turns was determined to be less than 0.02 ps, which agreed with the measurement results.

During harmonic cavity optimization, when a mismatch existed between the main RF cavity and harmonic cavity, stored bunches deviated significantly from their equilibrium positions due to large longitudinal kick forces. This resulted in coherent longitudinal dipole oscillations with substantial amplitude occurring at a frequency close to the stabilized operating frequency (normalized frequency of 0.005) of the main RF system after closed-loop operation. When such instability occurs, the beam signal amplitude exceeds the normal operating state due to coupling between longitudinal and transverse motions. These random events can be captured by setting appropriate signal trigger thresholds. To reduce random measurement errors, phase and bunch-length data for all 500 bunches were averaged, as shown in Fig. 8a [Figure 8: see original paper]. Analysis of the time-frequency domain characteristics of the oscillation waveform revealed that the frequencies of longitudinal phase oscillation and bunch length oscillation matched completely, but with opposite phases. The random error in turn-by-turn bunch-length measurements, obtained through multibunch averaging, could be reduced to less than 0.05 ps, and the sinusoidal bunch-length oscillation waveform with a peak-to-peak amplitude of approximately 1.5 ps could be perfectly reproduced. Analysis of bunch length and phase changes during instability revealed a strong negative linear relationship between the two, consistent with previous theoretical analyses.

V. DISCUSSION

For most electron storage rings serving synchrotron light sources or colliders, bunch lengths typically range from tens to hundreds of picoseconds. Based on simulation analysis and experimental results from this study, data acquisition systems with several gigahertz of analog bandwidth and tens of gigahertz sampling rate can fully meet the requirements for bunch-length measurement resolution. The developed bunch-length measurement system can be conveniently deployed and applied to any electron storage ring using commercial digital oscilloscopes and time-frequency-domain joint analysis.

For Gaussian longitudinal distributions with bunch lengths ranging from 20 to 200 ps, the turn-by-turn bunch length measurement uncertainty can be better than 1 ps for bunch charges greater than 400 pC, with a measurement dynamic range exceeding 10 ms. However, the single-bunch, single-turn bunch-length resolution has not yet reached a level suitable for all high-resolution beam experiments. Nevertheless, when focusing on the average bunch length among different bunches (such as the distribution of bunch lengths within a bunch train during steady-state operation), turn-by-turn measurement results for each bunch can be averaged to reduce random measurement error to less than 0.02 ps. When focusing on common-mode variations of all bunches in the storage ring (such as coherent longitudinal oscillations), measurement results for the same turn across multiple bunches can be averaged to reduce random measurement error to less than 0.05 ps.

The current time-frequency-domain joint analysis bunch-length measurement technique assumes a Gaussian bunch distribution, providing only the σ parameter as a characteristic measurement quantity. Therefore, it cannot fully replace streak cameras. When the longitudinal bunch distribution deviates from a standard Gaussian distribution (such as during filamentation in the damping process after injection or when significant wakefield effects produce an off-center Gaussian distribution), the results are approximate. Further improvements to the system sampling rate and obtaining more accurate measurements of the beam signal spectrum, coupled with appropriate data fitting models, may enable additional characteristic parameters to be used as measurement results and even allow reconstruction of the original time-domain distribution through inverse Fourier transformation.

VI. CONCLUSION

This study presents a novel technique for bunch-by-bunch bunch-length measurement utilizing time-frequency analysis of beam signals acquired by an oscilloscope. The method achieves a bunch-by-bunch, turn-by-turn bunch-length measurement uncertainty of 1 ps. In single-bunch experiments, results from the time-frequency analysis method closely matched those from streak cameras. In longitudinal instability studies, this technique effectively captured synchronous oscillations of bunch length and phase. During harmonic cavity tuning, the system successfully observed the cavity' s bunch stretching effect and accurately resolved sub-picosecond differences between bunches within a bunch train. Furthermore, experimental data verified a linear relationship between bunch-length changes and phase changes within a small range.

In summary, existing wideband high-speed oscilloscope technology meets the requirements for bunch-by-bunch and turn-by-turn bunch-length measurements.

The proposed time-frequency analysis technique using button electrodes enables precise measurement of longitudinal center position (phase) and bunch length, offering measurement resolution suitable for most experiments with bunch lengths above 20 ps. When the target bunch follows a Gaussian longitudinal distribution, the measurement system performance surpasses that of streak cameras (phase uncertainty better than 0.2 ps, bunch length uncertainty better than 1 ps, dynamic range exceeding 10 ms). This technique can be integrated as an additional module in the existing 3D bunch position measurement system HOTCAP, forming a comprehensive multiparameter bunch-by-bunch measurement system that includes position, bunch length, and charge. It can be directly applied to any high-energy electron storage ring and serves as a powerful diagnostic tool for studying beam impedance and nonlinear beam dynamics. Future work will focus on porting this technique to a processor-based platform to establish an online measurement system for real-time monitoring of beam parameter variations in storage rings.

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