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BUNCH-BY-BUNCH BEAM CURRENT AND LIFETIME MEASUREMENT WITH INTERLEAVED SAMPLING AT HLS*

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Abstract

To achieve high-precision, bunch-by-bunch beam current and lifetime measurements at the Hefei Light Source (HLS), we developed a beam diagnostics system based on interleaved sampling technology, achieving an equivalent sampling rate of 6.5 GHz. In single-bunch mode, amplitude extraction via cross-correlation with a single response function yields a turn-by-turn current relative resolution of 0.12 %. By averaging over 200 turns, the resolution is improved to 0.04 % at a 23 kHz data refresh rate, enabling fast and accurate lifetime calculations. However, in multi-bunch high-current mode, large longitudinal oscillations degrade the accuracy of amplitude extraction when using a fixed-response function. We propose an integration method to mitigate the effects of bunch length and phase oscillations on beam current measurements. The method and experimental results provide a practical solution for machines exhibiting large longitudinal oscillations, such as HLS.

INTRODUCTION

HLS is a dedicated second-generation VUV light source. It employs a top-up injection mode, with a typical beam current of 420 mA, a lifetime of 10 hours, and an RF frequency of 204 MHz. The existing bunch-by-bunch current measurement system uses a 4 GHz oscilloscope to sample the sum signal from the beam position monitor (BPM). The relative measurement error is 0.2 % [1].

High-precision, fast-response bunch-by-bunch beam current and lifetime measurements allow comprehensive analysis of single-bunch and bunch-to-bunch dynamics [2, 3]. To achieve this goal, a beam measurement system based on interleaved sampling has been developed, and its current measurement accuracy has been evaluated.

Significant longitudinal oscillations in the HLS beam cause continuous variations in bunch length and phase on a turn-by-turn basis, leading to changes in the response waveform of individual bunches. Currently, bunch-by-bunch current information is primarily obtained by measuring the amplitude of the BPM signal [4]. However, under dynamic variations in the response waveform, the signal amplitude no longer solely reflects the relative charge quantity but also incorporates information about changes in bunch length , phase, etc [5]. To mitigate the interference caused by large longitudinal oscillations on current measurement, this paper proposes a current extraction algorithm based on an integration method.

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MEASUREMENT SYSTEM SETUP

The structure of the phase-sampling-based bunch-by-bunch measurement system is illustrated in the Fig. 1. When measuring beam current, the system first combines the four electrode signals from the BPM into a single sum signal using a power combiner. This sum signal is then equally split into eight channels via phase shifters and fed into an eight-channel processor for synchronous acquisition. The phase-locked sampling clock is derived from a quadrupled-frequency signal of the RF system. A single bunch can be sampled at 32 points, corresponding to an equivalent sampling rate of 6.5 GHz. This architecture enables the system to measure bunch-by-bunch parameters such as bunch length, phase, and current. This paper focuses on evaluating its bunch current measurement capability. To assess the system's accuracy in this regard, we conducted experimental analysis of bunch-by-bunch current under single-bunch operation mode

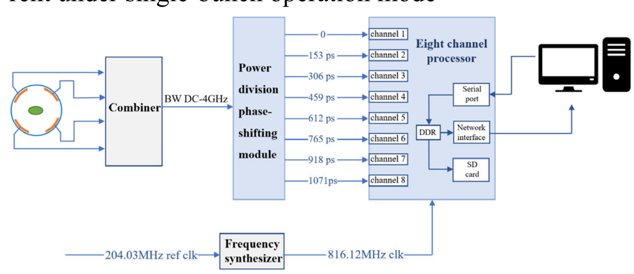

Figure 1: Architecture of the measurement system.

Single-bunch Mode

When a bunch with an current of 7.6 mA is injected, the signal waveform acquired through the eight-channel processor is shown in the Fig. 2.

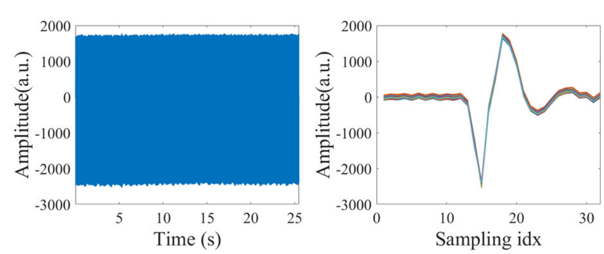

Figure 2: Single-bunch beam acquired signal.

Figure 2 displays the signals corresponding to 5200 consecutive turns of this single bunch. Under single-bunch operation mode, the influence of longitudinal bunch oscillations on the measurement is negligible. The relative variation in charge is characterized by extracting the signal amplitude at a fixed phase. Taking the peak value as an example, the resulting data is presented in the Fig. 3.

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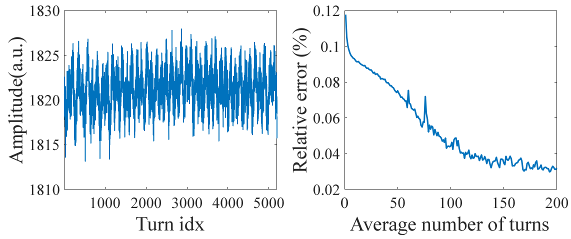

Figure 3: Amplitude extraction results.

The results in Fig. 3 demonstrate that in single-bunch mode, the relative turn-by-turn beam current measurement precision of this system reaches 0.12 %. By applying averaging over 200 consecutive turns, the measurement precision can be further improved to better than 0.04 %, achieving a corresponding beam current update rate of 23 kHz.

These results indicate that the system retains potential for further enhancement in measurement precision through appropriately increasing the number of turns used for averaging.

Top-up Mode

Measurements of the bunch output signals were conducted in top-up mode, with the turn-by-turn signal of one individual bunch extracted and shown in the Fig. 4.

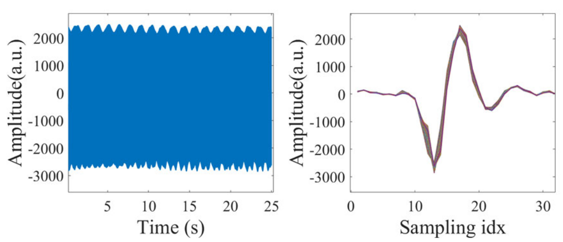

Figure 4: Extraction of a single bunch signal.

Within the measurement window, the bunch current exhibits no significant variation. However, as clearly observed in Fig. 4, the output waveform of this bunch undergoes continuous changes over time.

Figure 5 shows the extracted turn-by-turn peak values, bunch length, and phase [6].

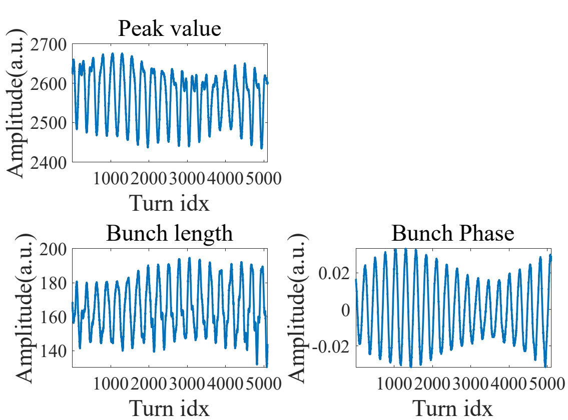

Figure 5: Peak value, bunch length and phase.

As shown in Fig. 5, the amplitude oscillation reflects variations in the signal waveform. This behavior is primarily attributed to changes in bunch length and phase caused by longitudinal beam oscillations. If the relative charge is characterized solely by a single amplitude value, the resulting turn-by-turn measurement error exceeds 2 %, which does not meet the required precision. For further analysis, Fig. 6 shows scatter plots comparing the amplitude with the bunch length and phase, respectively.

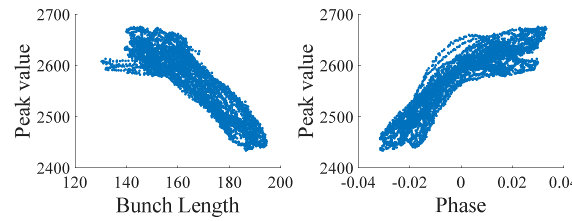

Figure 6: Scatter plot.

As clearly shown in the Fig. 6, distinct dependencies are observed. The Pearson correlation coefficients are calculated to be -0.89 with the bunch length and 0.90 with the phase, both indicating strong correlations.

Therefore, this paper utilizes an integration method, leveraging the sufficiently high sampling rate, to calculate the bunch-by-bunch beam current.

INTEGRATED CURRENT MEASUREMENT

In storage rings, bunches are typically modeled with a Gaussian distribution. Considering a bunch containing N electrons with a bunch length of σ_τ, the time-domain expression for a single bunch is given by [7]:

$$I_b(t) = \frac{eN}{\sqrt{2\pi}\sigma_\tau}\exp\left(-\frac{t^2}{2\sigma_\tau^2}\right). \tag{1}$$

The output signal after the beam passes through the pickup electrode results from the convolution of the differentiated original signal with the electrode's response function, expressed as:

$$V_b(t) = K\frac{dI_b(t-t_0)}{dt}, \tag{2}$$

where K represents the electrode response function. t_0 represents the offset of the beam phase.

The original signal can be reconstructed by integrating the output signal backwards:

$$U_b(t) = \int V_b(t)dt \propto I_b(t-t_0). \tag{3}$$

Performing further integration yields:

$$\int U(t)dt \propto \int I_b(t-t_0)dt = eN. \tag{4}$$

After double integration, the result corresponds to the area under the original signal curve, which represents the bunch charge. The integration method eliminates the influence of bunch length and phase, and does not require complex fitting procedures.

Numerical Simulation

A numerical simulation was conducted to validate the effectiveness of the integration method. The simulated Gaussian bunch had a charge of 1 nC and a bunch length

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of 100 ps. Under a sampling rate of 20 GHz, the discrete values after the beam passed through the button electrode and the result after the first integration are shown in Fig. 7.

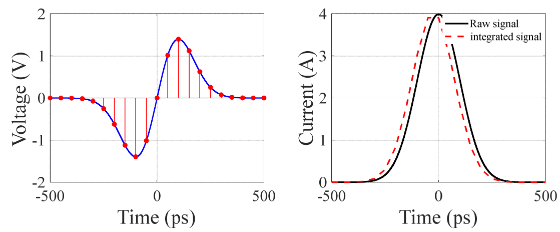

Figure 7: Simulation process.

The original signal was subjected to double integration. The trapezoidal rule was applied in both integration steps. The final calculated charge exhibited a relative error of only 0.0004 %, demonstrating that the method effectively utilizes limited discrete samples for accurate charge calculation.

To simulate the impact of beam phase offset and bunch length variation on charge measurement, the relative error was evaluated over phase shifts of [-50, 50] ps and bunch lengths of [90, 110] ps. The results are shown in Fig. 8.

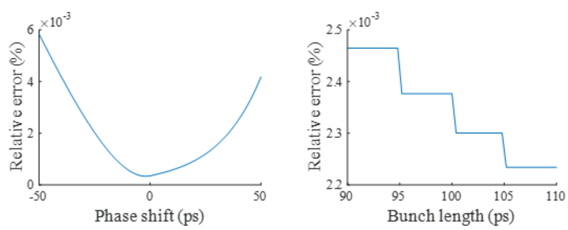

Figure 8: Results of bunch length and phase variations.

Figure 8 shows the charge can be measured with high precision even under variations in phase and bunch length.

Experimental Data

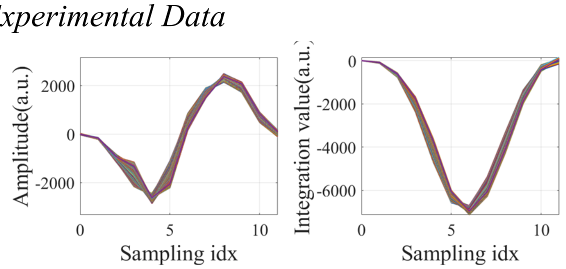

Figure 9: Integration interval.

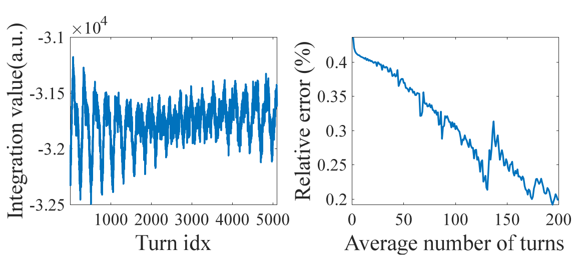

Figure 10: Result of the integration.

The charge was measured using the data from Fig. 4. The measurement utilized sampling points at the positions of the positive and negative peaks, which exhibit a higher signal-to-noise ratio, as illustrated in Fig. 9.

The relative turn-by-turn current values calculated by the integration method are shown in Fig. 10.

As shown in the results of Fig. 10, the integration method achieves a relative measurement error of 0.43 % for the charge quantity—a significant improvement over the peak extraction method. After averaging over 200 turns, the relative error is further reduced to below 0.2 %. Thus, the integration method effectively enhances the precision of charge measurement.

The Pearson correlation coefficient between the integrated value and the bunch length is 0.079, indicating almost no monotonic relationship. The correlation with the phase is -0.37, suggesting a weak negative correlation. Overall, the impact of variations in bunch length and phase caused by longitudinal oscillations on the beam current measurement has been significantly eliminated.

The remaining oscillations in the integrated value may be related to oscillations in the beam's transverse position. A spectral analysis of the integrated value was performed, and the results are shown in Fig. 11.

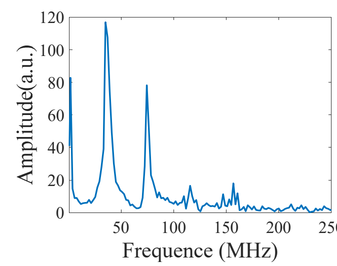

Figure 11: Spectrum analysis.

As observed in the spectrum, the influence of longitudinal oscillations remains evident. At the pickup electrode location, these oscillations may be coupled into transverse position variations through the dispersion function. Although the impact of bunch length and phase has been mitigated through integration, the variation in transverse position is difficult to remove via signal processing, as it reflects a real physical phenomenon [8]. This effect leads to fluctuations in the coupling strength at each electrode, causing the signal to carry oscillation information related to the transverse beam position.

Therefore, improving bunch-by-bunch current measurement accuracy requires further analysis of the transverse coupling induced by longitudinal oscillations.

CONCLUSION

A beam measurement system based on interleaved sampling technology has been developed, enabling turn-by-turn, bunch-by-bunch beam current measurements with a relative error of 0.12 %. Multi-turn averaging will further enable accurate beam lifetime measurement. The integration method for beam current calculation significantly reduces the impact of bunch length and phase variations caused by longitudinal oscillations on current measurement. The transverse beam position also considerably influences the measurement accuracy. Further compensation for this effect will be implemented to enhance the precision of beam current measurement.

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REFERENCES

[1] Y. L. Yang *et al.*, "HLS bunch current measurement system", *Sci. China Phys. Mech. Astron,* vol. 54, suppl. 2, s309-s312, 2011. doi: 10.1007/s11433-011-4519-2

[2] F. Z. Chen *et al.*, "Touschek lifetime study based on the precise bunch-by-bunch BCM system at SSRF", *Nucl. Sci. Tech,* vol. 30, pp. 144, 2019. doi:10.1007/s41365-019-0655-6

[3] Y. M. Deng *et al.*, "Current status and latest developments in electron storage ring bunch-by-bunch beam diagnostic techniques", *Nucl. Tech,* vol. 47, no. 10, 2024. doi:10.11889/j.0253-3219.2024.hjs.47.100201

[4] B. Gao *et al.*, "Bunch-by-bunch beam lifetime measurement at SSRF", *Nucl. Instrum. Methods Phys. Res. A,* vol. 1015, art. no. 165758, 2021. doi:10.1016/j.nima.2021.165758

[5] H. S. Wang *et al.*, "Technique for Extracting Initial Parameters of Longitudinal Phase Space of Freshly Injected Bunches in Storage Rings, and Its Applications", *Instruments,* vol. 9, no. 3, p. 17, 2025. doi:10.3390/instruments9030017

[6] H. S. Wang *et al.*, "Bunch-length measurement at a bunch-by-bunch rate based on time-frequency-domain joint analysis techniques and its application", *Nucl. Sci. Tech*, vol. 35, p. 80, May 2024. doi:10.1007/s41365-024-01443-z

[7] S. R. Gao, "Beam position monitor engineering", *AIP Conf. Proc,* vol. 390, no. 1, pp. 50-65, 1997. doi:10.1063/1.52306

[8] X. Yang *et al.*, "Determining beam transverse absolute position by triangulation of multi-electrode signal phase differences", *Nucl. Sci. Tech,* vol. 35, p. 133, 2024. doi:10.1007/s41365-024-01498-y