Introduction and Preliminary Study of the Hefei Light Source Storage Ring Bunch-by-Bunch Three-Dimensional Position Measurement System

Authors: Lu Ping, Tang Leilei, Sun Baogen, Fangfang Wu, Ruizhe Wu, Jigang Wang, Zhou Zeren, Lu Ping

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Abstract

The four-channel electrode signals from the beam position monitor (BPM) at the Hefei Light Source storage ring are directly connected to a domestic oscilloscope featuring 12-bit resolution, 10 Gsps sampling rate, and 2 GHz bandwidth. The acquisition program operates on a cloud host under the Zstack architecture. Upon each trigger, a waveform segment of 500 s is recorded, from which the X (horizontal position), Y (vertical position), and Z (longitudinal phase) information of the bunch centroids is extracted for 45 bunches over 2266 turns. The per-bunch resolution is approximately 5 m for X and Y, and approximately 0.5 ps for Z. The online operation update cycle is approximately 7 seconds. Spectral analysis of the obtained per-bunch three-dimensional position information can yield the three-dimensional tune of each bunch during normal operation, while analysis of the button and strip electrode signals can obtain the spectral peaks of quadrupole oscillations in transverse size during excitation.

Full Text

Introduction and Preliminary Study of a Bunch-by-Bunch 3D Position Measurement System for the Hefei Light Source Storage Ring

Lu Ping, Tang Leilei, Sun Baogen, Wu Fangfang, Wu Ruizhe, Wang Jigang, Zhou Zeran
National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China

The four electrode signals from the beam position monitor (BPM) in the Hefei Light Source storage ring are directly connected to a domestic oscilloscope with 12-bit resolution, 10 Gsps sampling rate, and 2 GHz bandwidth. The acquisition program runs on a cloud host under the Zstack architecture. Each trigger reads a set of waveforms 500 s long, extracting the X (horizontal position), Y (vertical position), and Z (longitudinal phase) information of the bunch centroids for 45 bunches over 2266 turns. The bunch-by-bunch resolution is approximately 5 m for X and Y, and about 0.5 ps for Z, with an online operation update cycle of around 7 seconds. Spectral analysis of the obtained bunch-by-bunch 3D position information yields the 3D tune of each bunch during normal operation, while analysis of button and strip electrode signals can reveal spectral peaks of the quadrupole oscillation of transverse dimensions during excitation.

Keywords: Hefei Light Source; bunch-by-bunch; 3D parameters; quadrupole oscillation; BBQ; EPICS; Zstack; caLab; LabView

System Overview

Observing the bunch-by-bunch 3D motion of beams in storage rings is highly significant [1][2]. Recent advances in instrumentation technology, particularly the achievement of domestic instruments whose performance metrics meet or exceed those of internationally established instruments commonly used at various light sources, combined with stability suitable for year-round online operation, have made it possible to measure bunch-by-bunch 3D motion information based on domestic oscilloscopes. This work utilizes a Siglent SDS6204 H12 Pro oscilloscope [3], with acquisition and processing programs developed in the LabView environment on a Windows 10 cloud host under the Zstack [4] virtual architecture. The program writes EPICS PV variables to a CentOS-based IOC via caLab, after which results are retrieved and displayed through an OPI.

Table 1 provides the parameters of the Hefei Light Source storage ring [5]. Figure 1 [Figure 1: see original paper] shows the layout of beam diagnostic components in the Hefei Light Source storage ring. This system measures the strip-line and button combined BPM at position number 7. Figure 2 [Figure 2: see original paper] illustrates the block diagram of the bunch-by-bunch 3D position measurement system.

For convenient comparison, two Siglent oscilloscopes of this model are used—one connected to the strip-line BPM and one to the button BPM. A frequency divider converts the 1 Hz timing system trigger signal into 0.1 Hz to serve as the oscilloscope trigger. Figure 3 [Figure 3: see original paper] shows the physical system layout. Figure 4 [Figure 4: see original paper] displays three sets of BPMs: the left two groups are on the same vacuum chamber section, with the left being the strip-line BPM and the right being the button BPM, connected to the two oscilloscopes respectively. The button BPM on the far right next to the quadrupole magnet is IVU1 from the COD system, connected to a Libera B+ processor [6].

Each trigger acquisition captures four waveforms 500 s long, with 5 million data points per channel. After removing non-integer-turn points at the beginning and end, the data contains integer-turn information for 2266 turns. Bunch-by-bunch timing information is extracted through zero-crossing interpolation, while amplitude information is obtained through methods such as finding the parabolic extremum using three points (the extremum and one point on each side) or simple integration and root-sum-square integration (the program also includes a fusion function for various methods, selectable or integrative fusion). The bunch-by-bunch horizontal and vertical positions (X, Y) are then calculated through difference-over-sum conversion. Additionally, the bunch-by-bunch current is calibrated using DCCT current data. In addition to publishing bunch-by-bunch information, the program also extracts turn-by-turn information for each bunch and publishes it via PV after spectral analysis, yielding each bunch’ s transverse and longitudinal tune information. The program also includes preprocessing options such as resampling and notch filtering, as well as SVD decomposition for component selection. The processing and publishing cycle for one set of waveforms is 7 seconds, with the main bottleneck being waveform reading. The four waveforms of 5 million points each constitute 40 MB of data, requiring 7 seconds to fully read from the oscilloscope into the cloud host at an average speed of 5.7 MB/s. To enable comparative analysis of waveforms from both oscilloscopes from the same time period, a frequency divider trigger is used with a 10-second period. The program interface is shown in Figure 5 [Figure 5: see original paper].

Measurement Results

After obtaining bunch-by-bunch X, Y, and Z information from a set of waveforms, the 3D positions of 45 bunches over 2266 turns can be displayed through three-view projections. Alternatively, to examine specific bunch-by-bunch information, the bunch number and turn number can be used as coordinates in a 2D plot, with the information displayed through different colors (ripple plot). Figure 6 [Figure 6: see original paper] presents ripple plots that intuitively reveal longitudinal oscillations.

The left panel of Figure 6 shows a 2D plot of bunch-by-bunch current, with the lower curve representing the average current over 2266 turns for each bunch. The middle curve shows the turn-by-turn current summed over all 45 bunches. The right panel displays the 2D plot of longitudinal timing.

Figure 7 [Figure 7: see original paper] shows ripple plots of X, Y, and I for strip-line and button BPMs during injection, with spectra below revealing the tune. The three-view projections provide an intuitive view of each bunch’ s motion. Figure 8 [Figure 8: see original paper] shows normal operation status, while Figure 9 [Figure 9: see original paper] shows injection status. In the three-view projections, the left set represents the strip-line BPM and the right set represents the button BPM, with different colors indicating different bunches. The topmost red point cluster represents the distribution of turn-by-turn coordinates averaged over 45 bunches in the three-view projection.

Error Analysis

Observation of the three-view projections reveals that bunches exhibit noticeable circular motion in the top view due to longitudinal oscillations coupling into the X direction, with similar phenomena sometimes observed in the front view. After removing the low-frequency circular motion components, measurement errors can be analyzed by calculating the standard deviation (STD). The three panels in Figure 10 [Figure 10: see original paper] show the distribution of a selected bunch’ s measurements after subtracting the low-frequency circular motion components, yielding STD values of approximately 3.8 m for X, 4.2 m for Y, and 0.4 ps for Z. These values are similar across different bunches and waveform sets, and are rounded up to 5 m, 5 m, and 0.5 ps respectively.

The bunch-by-bunch X and Y from one waveform set (500 s) can be successively averaged to obtain turn-by-turn, FA (fast acquisition at 44 kHz), and MA (medium acquisition at 2 kHz) data. Since the two oscilloscopes are synchronized for comparison with a 10-second processing period, if one X, Y pair is obtained per 500 s waveform, this is equivalent to a 2 kHz signal (similar to MA) sampled once every 10 seconds. To compare with the SA (10 Hz) measurements from Libera B+, 200 points sampled from the 2 kHz signal must be averaged.

Figure 11 [Figure 11: see original paper] shows the STD results obtained online during operation through successive averaging of a waveform set. Figure 12 [Figure 12: see original paper] displays the online status of the COD system measured by Libera B+. The SA data STD for X and Y from the 32 BPMs in the COD system measured by Libera B+ is within 1 m. The SA STD obtained through rolling averaging of the oscilloscope data is comparable. The turn-by-turn and FA data from a single waveform set are better than MA and SA data, primarily because the STD for turn-by-turn and FA is calculated from statistics within a single 500 s waveform set, whereas MA and SA statistics are from different waveform sets over longer periods.

Figure 13 [Figure 13: see original paper] compares continuous 2.5-day monitoring of SA from the oscilloscope and Libera B+. Figure 13(a) shows the horizontal direction X, with the green curve from Libera B+ measuring IVU1, blue and orange from button and strip-line respectively, and red from DCCT. Figure 13(b) shows the vertical direction Y, with the blue curve from Libera B+ measuring IVU1, orange and green from button and strip-line respectively, and red from DCCT. The long-term comparison shows Libera B+ remains stable within 3-4 m. Ignoring regions with large current variations, the oscilloscope X drifts within 20 m and Y within 10 m, likely related to the oscilloscope’ s temperature control measures and the lack of crossbar switching to eliminate channel inconsistencies during long-term operation, resulting in current-dependent effects (particularly more severe in X).

Figure 14 [Figure 14: see original paper] compares 24-hour continuous monitoring of oscilloscope MA and Libera B+ SA with the COD orbit feedback system turned off, allowing free orbit drift. The red curve is Libera B+ measuring IVU1, orange and green are button and strip-line respectively, and blue is DCCT. Figure 14(a) shows horizontal X, and Figure 14(b) shows vertical Y.

Preliminary Analysis Results

Tune Measurements

Figure 15 [Figure 15: see original paper] shows spectra of X and Y without beam. Noise peaks appear at approximately 350 kHz and its harmonics in the X and Y spectra without beam, generated during amplitude extraction calculations. These spectral peaks can be ignored when examining spectra with beam present.

Figure 16 [Figure 16: see original paper] shows spectra during normal operation. In the spectra, the upper Turn-By-Turn plot is the sum of spectra from all 45 bunches. The Hefei Light Source revolution frequency is $f_0 = 4.534$ MHz, so the visible spectral range is $0\sim f_0/2 = 2.267$ MHz. The lower Bunch-By-Bunch plot shows the spectrum of bunch-by-bunch X and Y, with a visible range of $0\sim 45\times f_0/2 = 102$ MHz. The tune peaks are visible in Figure 16. The signal-to-noise ratio and resolution are generally better than BBQ system spectra. Except for the tune peaks corresponding to BBQ spectra, other peaks match exactly the noise peak positions shown in Figure 15. Bunch-by-bunch data enables analysis of each bunch’ s tune.

Figure 17 [Figure 17: see original paper] shows histograms of tune frequencies for 45 bunches in X, Y, and Z. The horizontal tune has an average frequency of 2.0094 MHz, corresponding to a fractional tune of 0.4432. The vertical tune has an average frequency of 1.6732 MHz, corresponding to a fractional tune of 0.3690. The longitudinal tune has an average frequency of 14.44 kHz, corresponding to a tune of 0.0032.

Relationship Between Transverse Quadrupole and Dipole Oscillations

Transverse dipole oscillations of beams in storage rings represent collective beta oscillations of particles, with oscillation frequencies corresponding to the tune frequencies, expressed as $f_0(\pm\Delta)$, where n is an integer and Δ , Δ are the horizontal and vertical fractional tunes respectively. f_0 is the revolution frequency. Transverse beta oscillations reflect the storage ring’ s transverse focusing lattice structure, while transverse quadrupole oscillations reflect beam intrinsic properties. To describe the relationship between transverse quadrupole and dipole oscillations, particle-like sinusoidal oscillations are simplified to sinusoidal oscillations. As shown in Figure 18 [Figure 18: see original paper], consider the motion of two particles initially farthest apart in the horizontal direction within a single bunch.

Transverse quadrupole oscillations of a bunch correspond to oscillations of the bunch’ s transverse dimensions. As shown in the diagram, when the bunch’ s horizontal dimension completes one oscillation period, the two particles initially farthest apart in the horizontal direction have each only completed half a beta oscillation period. The particle beta oscillation frequency can be expressed as $f_0(\pm\Delta)$, yielding a transverse quadrupole oscillation frequency of $2f_0(\pm\Delta)$.

Extracting Transverse Quadrupole Signals from Strip-line BPM

Three strip-line and button combined BPMs are installed in the Hefei Light Source storage ring. A cross-sectional schematic of the strip-line BPM is shown in Figure 19 [Figure 19: see original paper], revealing four axisymmetric electrodes.

Where V_R, V_L, V_T, V_B are the induced voltage signals on the right, left, top, and bottom electrodes of the strip-line BPM respectively. When the four BPM electrodes are orthogonally symmetric, formulas 1 and 2 are satisfied. The beam’ s transverse quadrupole signal can be calculated through the following formula (difference-over-sum method):

Q_Δ/Σ is the calculated beam transverse quadrupole signal, representing the difference-over-sum of diagonal electrode signals. From formulas 1 and 2, when diagonal electrodes are summed and differenced, only the Z^2 term is amplified while other terms cancel out.

For non-orthogonally symmetric cases, the quadrupole signal can also be calculated through diagonal electrode sum and difference, though incomplete cancellation of terms other than Z^2 occurs due to different effective angles ϕ and distances b to the center for electrodes in the two directions. The relationship between the beam’ s transverse quadrupole signal and beam position (x_0, y_0) and transverse dimensions (σ , σ) can be expressed as:

Q_Δ/Σ = Q_S$(x_0, y_0, \sigma , \sigma)$

Where Q_0 is a DC signal generated because the four strip-line BPM electrodes are not orthogonally symmetric (only axisymmetric, with different horizontal and vertical electrode spacing). S_Q is the sensitivity for calculating transverse quadrupole signals based on strip-line BPM. (x_0, y_0) is the beam transverse position, and (σ , σ) are the beam transverse dimensions. For BPMs rotated 45° with orthogonal symmetry, quadrupole signals can also be calculated this way, though (x_0, y_0) and (σ , σ) in the formula should be coordinates and dimensions relative to the rotated coordinate system. If the bunch has strong transverse quadrupole oscillations, the Q_Δ/Σ spectrum will also be within the f_0 range. Corresponding to the Hefei Light Source tune, spectral peaks can be seen near frequencies such as 515 kHz and around $f_0(\pm\Delta)$ at approximately 1.188 MHz (σ), 3.346 MHz (σ), and 4.019 MHz (σ).

Figure 20 [Figure 20: see original paper] shows the Q_Δ/Σ spectrum during normal operation, and Figure 21 [Figure 21: see original paper] shows the Q_Δ/Σ spectrum during injection. In Figure 20, the pink curve is from the button BPM and the olive curve from the strip-line BPM. Except for spectral peaks generated by noise signals, no quadrupole oscillation peaks are visible during normal operation. Figure 21 shows Q_Δ/Σ spectra during injection. The Hefei Light Source injects horizontally, generating horizontal quadrupole oscillations during injection. The position marked QX in the figure corresponds to the horizontal quadrupole oscillation spectral peak from σ variations. The Turn-By-Turn spectrum only shows the lower sideband, while the Bunch-By-Bunch spectrum shows both symmetric upper and lower sideband quadrupole oscillation peaks. The Q_Δ/Σ quadrupole oscillation amplitude from the strip-line BPM is comparable to the amplitude at the tune position, visible on a linear scale, while the button BPM' s amplitude is about two orders of magnitude smaller, requiring a logarithmic scale for visibility. Both figures use logarithmic scales for strip-line and button BPMs.

Summary and Outlook

This bunch-by-bunch centroid 3D measurement system has been operating online at the Hefei Light Source. Based on its processed data, the 3D (transverse and longitudinal) tune of each bunch can be obtained during normal operation. Through analysis of BPM signals, spectral peaks of bunch transverse dimension quadrupole oscillations during injection can be obtained. Further analysis of data from this system is expected to yield additional results.

Although horizontal quadrupole oscillation spectral peaks during injection are visible, more detailed size variation patterns require future construction of a bunch-by-bunch 6D (centroid + dimension) measurement system for further observation. Building the system is only the beginning; further data analysis and information mining require participation from more interested researchers.

The developed program, currently at version 1.0.X, can conveniently set filling patterns and other parameters for universal application at various light sources. With minor modifications and additions, it can also be used for the upcoming oscilloscope-based bunch-by-bunch 6D (centroid + dimension) measurement system. The program is now open-source on gitee [9] and welcome for use by partner institutions.

It is worth mentioning that during the six months from initial system construction to current online operation, the virtual machine running under the domestic Zstack virtual architecture has maintained stable operation under high network and signal processing loads without ever crashing. The domestic Siglent oscilloscope has also never experienced downtime or unexpected connection interruptions, with all stops being manual for program improvement and debugging. Domestic software architecture and instruments have fully satisfied the demanding requirements of long-term online operation in major scientific projects.

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Note: Figure translations are in progress. See original paper for figures.

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