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A PRELIMINARY DESIGN OF BUNCH-BY-BUNCH 3D POSITIONS MEASUREMENT

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Abstract

The decrease of beam emittance in the 4^{th} generation light source greatly increases the electron density, thus the wakefields and beam impedance in the storage ring are significantly enhanced, resulting in various beam instabilities. Therefore, it is necessary to observe the transient state of beams using the bunch-by-bunch technique, so as to dig into these instabilities. Here a three-dimensional (3D) positions measurement instrument is designed based on data synchronization module (DSM) to acquire the transverse positions and longitudinal phases of beams in real-time.

INTRODUCTION

Compared with the 3^{th} generation light sources, the 4^{th} generation light sources are generally built with compact MBA structures, so that the horizontal emittance of the beam is reduced by 1 to 2 orders, close to the X-ray diffraction limit. Consequently, the strong nonlinear elements in the MBA structures make the dynamic aperture significantly smaller, causing the beam dynamics to be extremely sensitive to the effects of instabilities, and even affecting the maximum beam current during operation time. Hence, it is essential to observe the beam characteristics on fine time scales using bunch-by-bunch technique, figuring out the instabilities induced by wakefields, and even eliminating these instabilities.

Generally, bunch-by-bunch technique covers bunch length, longitudinal phase, bunch charge, transverse positions and bunch profiles [1–5]. However, it is obvious that these measurements are limited by the number of sampling channels on a single acquisition board, and only one single beam parameter can be obtained, rather than multiple parameters simultaneously. In order to break through the limitation of the number of sampling channels, a bunch-by-bunch 3D positions measurement instrument is designed with DSM [6], as shown in Fig. 1.

The instrument is mainly composed of microwave components and digital logic components, in which the microwave components are divided into signal part and timing part. For the signal part, it duplicates the four-channel signal sensed from the BPM in the storage ring and sends the two duplicated four-channel signals to data acquisition boards. For the timing part, the synchronous signal generated from the storage ring timing system is frequency quadrupled and then divided into two channels to data acquisition boards, between which there is a certain phase difference due to the delay

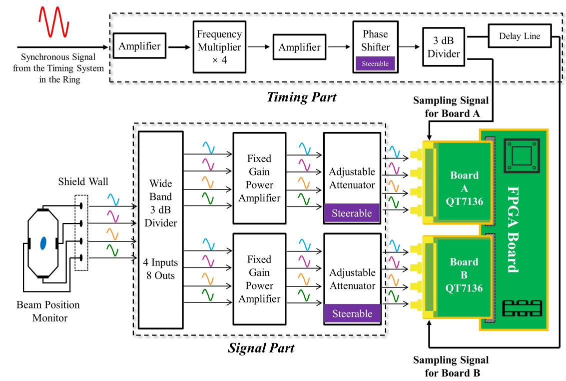

Figure 1: The layout of bunch-by-bunch 3D positions measurement instrument.

line. As for the digital logic components, two four-channel signals are digitized by the acquisition boards, then these digitized signals are synchronized by the DSM in FPGA, and finally the 3D positions of each bunch are calculated. Since these microwave components are at the factory, an evaluation system based on oscilloscope is set up to research the 3D positions measurement processes in the designed instrument.

EVALUATION SYSTEM SETUP

In order to determine the measurement performance in the 3D positions, an oscilloscope-based performance evaluation system was constructed, as shown in Fig. 2. With the help of the low-pass filter, the bandwidth of the oscilloscope is equivalent to that of the acquisition board, so that the data obtained by the oscilloscope and the data acquisition board are consistent. After the acquisition, these data will be sent to the computer for processing, and finally obtain the signals of each bunch during the bunch interval [7]. Finally, the corresponding measurement performance can be obtained by analyzing the signals in the bunch interval.

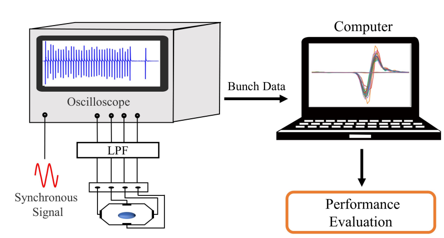

Figure 2: Evaluation system based on oscilloscope.

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3D POSITIONS MEASUREMENT

For longitudinal phases of bunches, its measurement formula is shown as Eq. (1) [7]:

$$L = K \cdot V_{OSM} \tag{1}$$

Where coefficient K represents the linearity of the BPM sum signal, which is determined by the amount of charge and the length of the bunch, and V_{OSM} is the BPM sum signal at one sampling point during the bunch interval.

However, this measurement method of longitudinal phases is susceptible to the jitters of the synchronous signals, so that the V_{OSM} obtained has a certain deviation from the actual, for whose detailed information please refer to Ref. [7]. To eliminate the influence of the clock jitters on longitudinal phases, it is necessary to adopt a two-point sampling method as shown in Fig. 3.

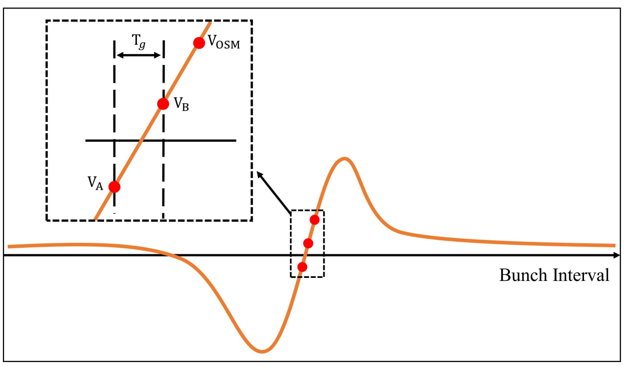

Figure 3: Sampling with two points in the bunch interval.

In the two-point sampling method, T_g is determined by the length of the delay line in the instrument, and the amplitude of the two sampling points V_A and V_B are completely determined by the BPM sum signals collected by the acquisition board A and B. Hence, the factor K in Eq. (1) can be completely determined, as Eq. (2):

$$K = (V_B - V_A) / T_g \tag{2}$$

While the value of V_{OSM} in Eq. (1) can also be determined by V_A and V_B, although the two sampling points corresponding to V_A and V_B have certain clock jitters. For one bunch in a specific filling pattern, the data relations $(V_A, V_B) - V_{OSM}$ can be constructed according to the bunch-by-bunch data collected by the oscilloscope-based evaluation system, as shown in Fig. 4.

In this way, with the data relations $(V_A, V_B) - V_{OSM}$, the vector $V_M(V_A, V_B)$ collected by the instrument in real-time is carried out with multiple vectors $V_D(V_A, V_B)$ in the data relations as shown in Eq. (3), and the corresponding data V_{OSM} is selected as the actual V_{OSM} when the matching coefficient M is the highest one.

$$M = (V_M \cdot V_D) \,/\, (|V_M| \cdot |V_D|) \tag{3}$$

Thus, the longitudinal phases L of each bunch can be obtained by two sampling points (V_A, V_B) without the effects

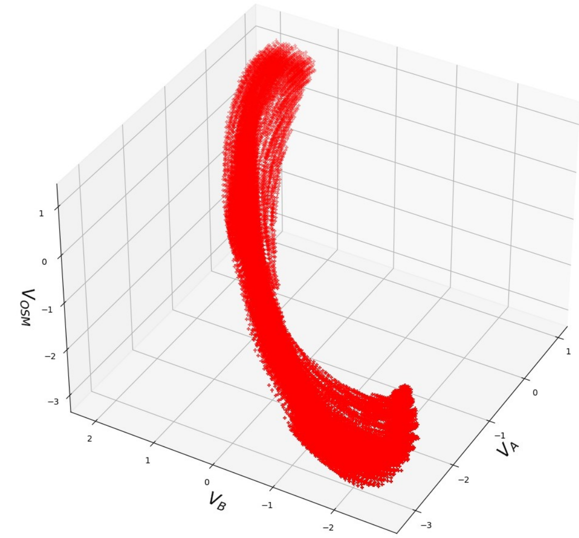

Figure 4: Relations between (V_A, V_B) and V_{OSM}.

of clock jitters. Moreover, it is worth noting that the data relations $(V_A, V_B) - L$ can be directly constructed, then the corresponding longitudinal phase L of the bunch can be directly calculated through Eq. (3), as depicted in Fig. 5. Here the red line shows the actual longitudinal phase of the bunch, while the blue line is the longitudinal phase of the bunch obtained through the data relations $(V_A, V_B) - L$.

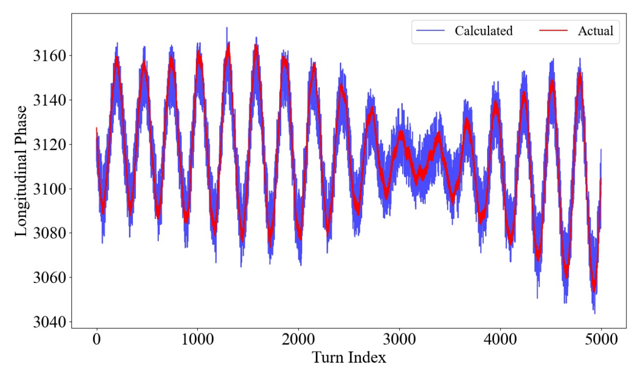

Figure 5: The actual longitudinal phases and the longitudinal phases calculated with relations.

As for the transverse positions of bunches, they are calculated with the $\Delta - \Sigma$ method, but using the four-channel signal whose BPM sum signal is larger between V_A and V_B to ensure the signal-to-noise ratio. The related equations are as follows:

$$\begin{cases} T_{x/y} = K_{x/y} \cdot \left(V_1 - V_{2/4} - V_3 + V_{4/2}\right) \cdot \frac{1}{\sum_{i=1}^{4} V_i} \\ V_i = V_{Ai} \text{ if } V_A > V_B \text{ else } V_{Bi} \end{cases} \tag{4}$$

Wherein: x/y is the transverse position of x-direction or y-direction, $K_{x/y}$ is a constant with unit "mm" depending on the geometry of button BPM, V_i are the digitized four-channel signals from BPM, and the subscript i indicates

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the identifier of the four channels. Besides, V_{Ai} and V_{Bi} represent the four-channel signals on sampling points A and B respectively.

DISCUSSION

Using the two-sampling method, the evaluation for the resolution of the transverse positions makes no difference from our previous work [7]. While for the resolution of the longitudinal phases, the error transfer formula is hard to obtain precise results due to the non-formulaic form of the data relations $(V_A, V_B) - V_{OSM}$. In view of this, there are two ways to acquire the actual resolution of the longitudinal phases:

- Construct the formula for $(V_A, V_B) - V_{OSM}$.
- Utilize data dimensional reduction methods.

For the first way, its essence is still the error transfer formula, but the construction is difficult. As for the second way, the longitudinal phases of the bunches obtained through data relations $(V_A, V_B) - V_{OSM}$ are processed for dimensional reduction, and the data variance before and after dimensional reduction is taken as the resolution assessment. However, it has subjective judgment factors in the dimensionality reduction.

Moreover, the data processing flows for 3D positions measurement can be basically determined, as shown in Fig. 6. After these digitized BPM signals are synchronized by the module DSM, the BPM sum signals (V_A, V_B) at two sampling positions in the bunch interval will be sent to the vector matching module to complete the calculation of Eq. (3) to find the most matched data relation $(V_A, V_B) - L$, and the matched L is taken as the longitudinal phase of the bunch. At the same time, the sampling selection module will select the four-channel signal whose BPM sum signal is lager as the input of the $\Delta - \Sigma$ module, which outputs the transverse positions of the bunch.

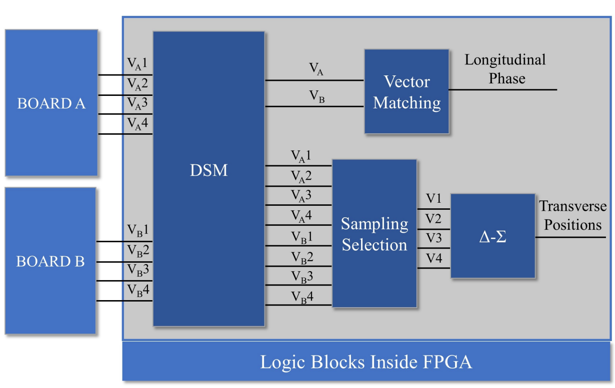

Figure 6: Data processing flows inside the 3D positions measurement device.

It should be noted that the construction of the vector matching module requires a large number of data relations $(V_A, V_B) - L$, in which the machine learning is needed to determine the vector matching parameters of each bunch in the filling pattern. Therefore, it is necessary to collect mass data with the oscilloscope-based evaluation system and then build its corresponding relations before building this bunch-by-bunch 3D positions measurement instrument, otherwise the measurement results will have a deviation. As revealed in Fig. 5, part of the reason why the longitudinal phases of the bunch calculated by vector matching module deviate from the actual longitudinal phases is owe to the insufficient amount of data relations $(V_A, V_B) - L$. But it is not ruled out that these deviations are also caused by inconsistencies of the movements of the bunches in the specific filling modes. Anyway, the two reasons need to be verified later through building sufficient data relations.

CONCLUSION

To design the instrument for observing the 3D positions of bunches in the storage ring, one oscilloscope-based evaluation system is set up to determine the data dealing processes of the 3D positions, and the framework of the logic blocks inside FPGA. However, there is some deviations between the longitudinal phases obtained with the vector matching and the actual longitudinal phases, which is due to the insufficiency of the data relations, or the inconsistency of the movement laws of the bunches in the specific filling mode. More research work is need to verify the two possibles.

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