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ON-LINE CROSSTALK MEASUREMENT AND COMPENSATION ALGORITHM STUDY OF SXFEL DIGITAL BPM SYSTEM*

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Abstract

Shanghai soft X-ray Free Electron Laser (SXFEL) has acquired the custom designed Digital BPM processor used for signal processing of cavity BPMs and stripline BPMs. In order to realize monitor the beam position accurately, it has high demand for DBPM system performance. Considering the crosstalk may introduce distortion and influence beam position resolution, it is important to analyze and compensate the crosstalk to improve the resolution. We choose the CBPM signal to study the crosstalk for its narrowband and sensitive for phase position. The main experiment concept is successive accessing four channels to form a signal transfer matrix, which including amplitude frequency response and phase response information. And the compensation algorithm is acquire four channel readouts, then using the signal transfer matrix to reverse the true signal to ensure the accurate beam position measurement. This concept has already been tested at SXFEL and hopeful to compensate the crosstalk sufficiently.

BACKGROUND

SXFEL

SXFEL is one of the high-gain FELs constructed in China. Key technologies have been tested through prototype developments. Based on the research and development prototype of hard X-ray FEL. The construction of the user facility in soft XFEL has already finished. The SXFEL facility consists of an electron injector with a thermionic cathode, main accelerate section including C-band high-gradient accelerators along with S-band accelerators, and in-vacuum undulators. Figure 1 is SXFEL undulator layout [1, 2].

SXFEL is designed to generate a coherent x-ray beam using a self-amplified spontaneous emission (SASE) process. In order to meet the harsh demands, the beam diagnostic system achieving high precision resolution is one of the most important technical issues. Cavity BPM meets the hash demands for the precise measurement of the resolution of the SXFEL undulators system. Figure 2 is the picture of one Cavity BPM installed in the tunnel.

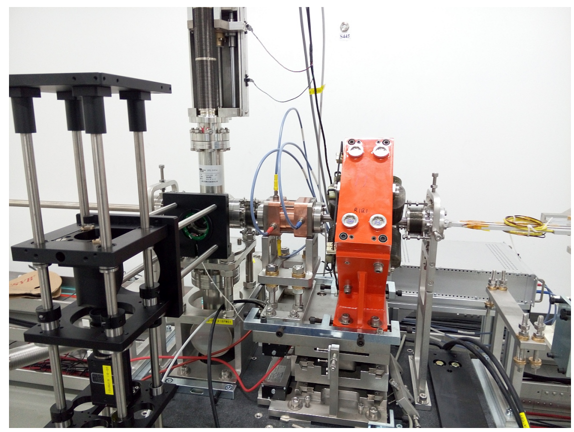

Figure 2: Cavity BPM installation spot picture.

Cavity BPM CBPM is a key beam instrumentation component for SXFEL beam diagnostics. As the requirement of undulator should reach sub-micron level position resolution. The high Q cavity BPM. As the key beam diagnostics tool, BPM systems are widely equipped in all kinds of accelerators. Cavity Beam Position Monitors are main beam diagnostic instruments in SXFEL. There are more than 20 CBPM conducted in SXFEL used for the measurement and adjustment of beam orbit. Moreover, the sum of four SBPM electrodes signal can also apply in relative beam charge measurement. RF cable extract beam signal from CBPM pickup, RF front-end module modulated signal to proper amplitude, then led the signal to digital BPM processor.

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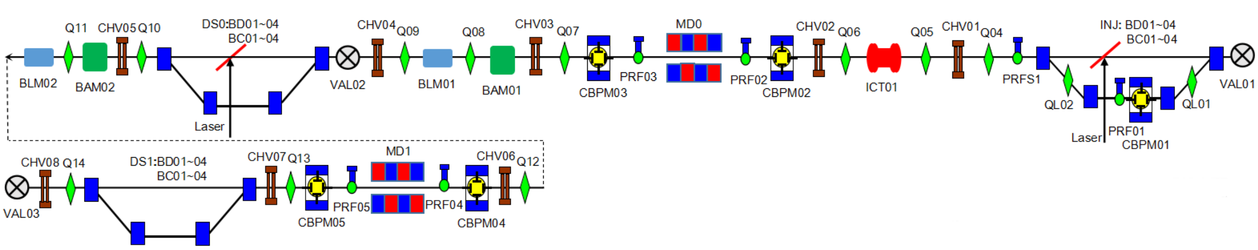

Figure 1: Partial layout of SXFEL undulator.

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Digital BPM Processor The Digital BPM processors are custom designed to measure the beam positions, every cavity beam position monitor is connected to a digital BPM processor. The centre frequency of the DBPM processor is 500 MHz, and the bandwidth is 20 MHz. The processor is consists of the RF pre-processing module and the analog to digital conversion module. The ADC conversion module carried a 16 bit high-resolution ratio ADC and advanced FPGA chip. The analog board of the DBPM has many analog devices and circuits, which may form considerable crosstalk. Figures 3 and 4 show the simplified architecture of the processor.

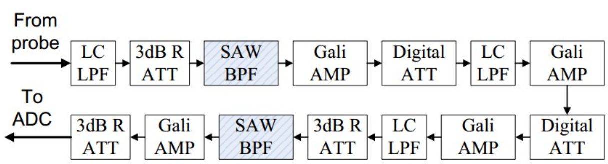

Figure 3: Analog devices module of DBPM processor.

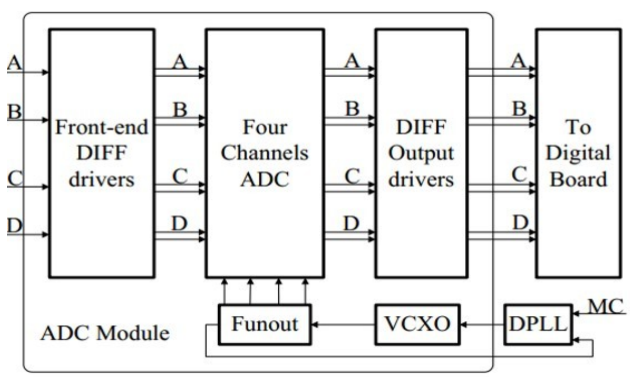

Figure 4: ADC module of DBPM processor.

BEAM EXPERIMENT

Target of Beam Experiment

One of the most important technical issues of the DBPM processor is to acquire high-fidelity signal. The beam position resolution in SXFEL BPM system should be better than sub-micron. Considering the crosstalk may introduce distortion and influence beam position resolution, it is important to analyze and compensate the crosstalk to improve the resolution.

Experiment Details

At normal SXFEL machine running status, we select one Cavity BPM reference cavity readout signal for the amplitude of signal is bigger and position independent. The architecture of experiment is shown below Fig. 5.

It consists of cavity BPM, DBPM processor and upper computer. The first experiment is measuring channel crosstalk in sequence. Signal from Cavity BPM successive guide into four channels of DBPM processor while other

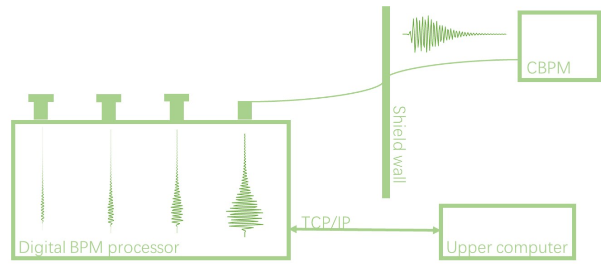

Figure 5: The architecture of the crosstalk calibration platform.

channels have impedance matching, host computer access four channels readouts at the same time. The upper computer carry Linux operating system, using python script to acquire the beam position data from the DBPM processors. The second experiment is using two channels of DBPM processor to access cavity BPM position.

EXPERIMENT ANALYSIS

Figure 6 is the experimental result of fours channels at successive signal input. According to the experimental data, the crosstalk at adjacent channels is obviously. The crosstalk of both sides are smaller than middle due to the placement and routing of the analog board. The most significant crosstalk is between channel B and channel C. After deep analysis, the variance of noise background is 38.05, while the variance of crosstalk section is up to 740.77. Figure 7 is the spectrogram of the channel B and channel C.

Principle Component Analysis

Although there is crosstalk between channels, however the amplitude of the crosstalk and the noise background are on the same scale. It's difficult to measure crosstalk using simple algorithm. The principal component analysis (PCA) method is introduced to analysis the experimental data. PCA is a powerful data analysis tool, capable of extracting useful information hidden in noise and doing pattern separation. Accumulation of 1024 experiment data samples of four channels, readouts of each channel contains characteristics of signal and crosstalk. The characteristics have complicated correlation relationships with each other, which makes it possible for dimensionality reduction with PCA. For convenience of description, let the 4×512×2048 matrix X denote the signal containing the crosstalks. The key point of PCA is how to derive the crosstalk from noise background. Figure 8 is the mode index of matrix X. Figure 9 is the pattern separation.

Principle of Measurement

The voltage signal coupled to the mid-end impedance Z is expressed as Eq. (1):

$$V_{out} = \frac{\omega q}{2}\sqrt{\frac{Z}{Q_{next}}\left(\frac{R}{Q}\right)_0} exp\left(-\frac{\omega^2\sigma_z^2}{c^2}\right)\frac{x}{x_0}, \quad (1)$$

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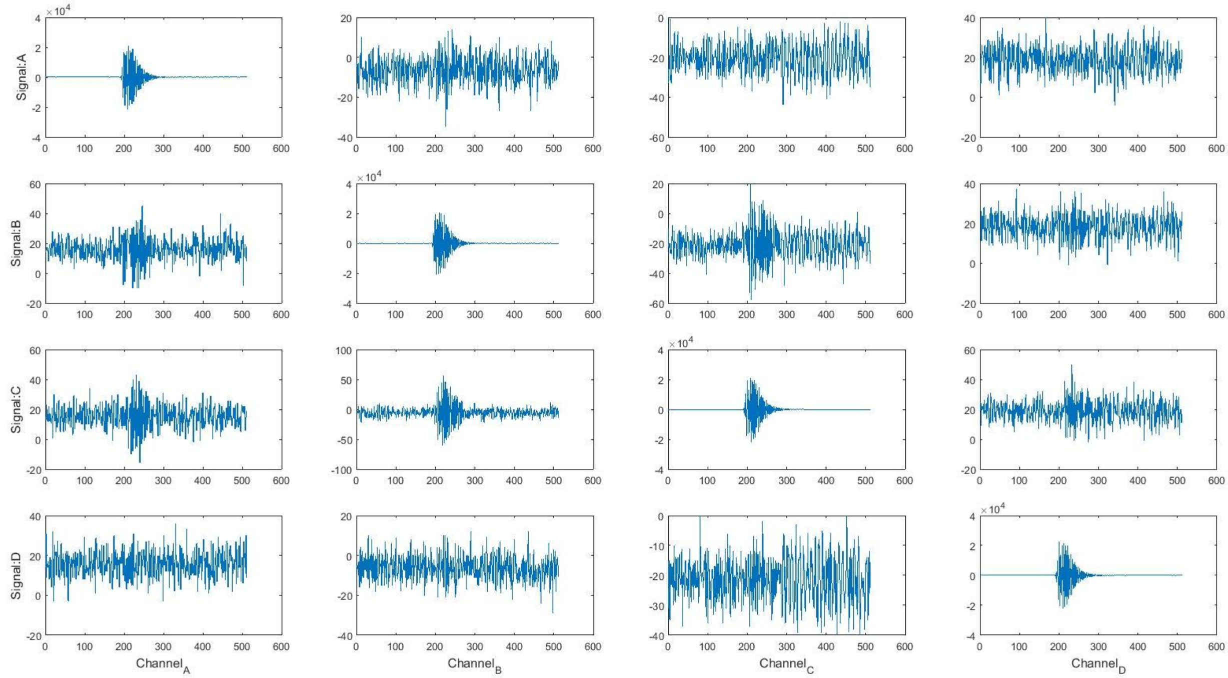

Figure 6: Crosstalk result of four channels at successive signal input.

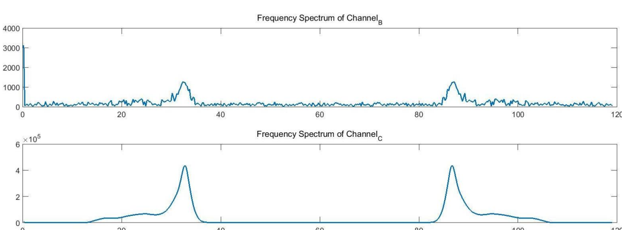

Figure 7: The spectrogram of the channel B and channel C.

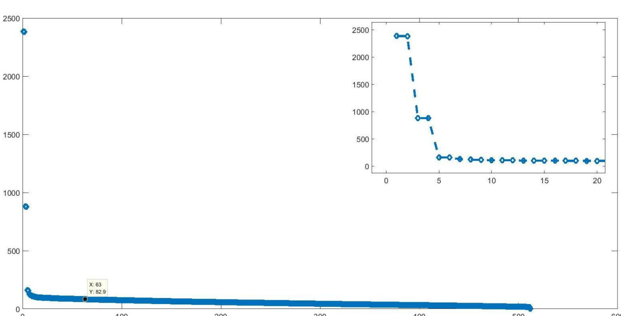
Figure 8: Eigenvalue distribution.

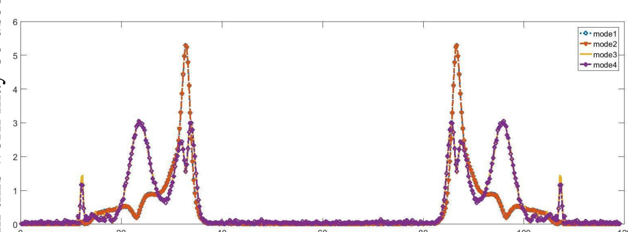

Figure 9: Pattern separation.

where R is the radius of the cavity, c is the electric field density, ω is the angular frequency of the resonance,σ_{beam} is the RMS width of the source spot, σ_z is the length and q is the charge of the Gaussian distribution bunch, $\frac{R}{Q}$ is the shunt impedance when the beam current is deviated from the electrical center of the cavity. The expression of the signal in the time domain is as Eq. (2):

$$V(t) = V_{out} e^{-\frac{t}{2\tau}} sin(\omega), \tag{2}$$

where $\tau$is the attenuation constant of the signal [3].

Considering the system is linear time invariant, we acquire a simplfy system. Assuming the expression of signal is $f(t)$, then the crosstalk is $kf(t')$. According to PCA, statistical procedure to elucidate the underlying covariance structure in the multidimensional data. Eigenvector of the largest four eigenvalue presents the I,Q component of the signal and the crosstalk. The crosstalk component is extracted from the backgroud noise, the specific value of amplitude is 0.0022. The sampling frequency is 119 MHz, phase difference covert to time delay is 67.2 ns. Figure 10 is the rough crosstalk compensation result.

CONCLUSION

In this article, we introduce the SXFEL digital BPM system. In order to evaluate the crosstalk performance of the SXFEL digital BPM system, we designed two experiments and introduced PCA to measure the crosstalk. The crosstalk of SXFEL digital BPM system is better than 57.76 dB, the distortion and influence introduced by the crosstalk is within the allowable error range.

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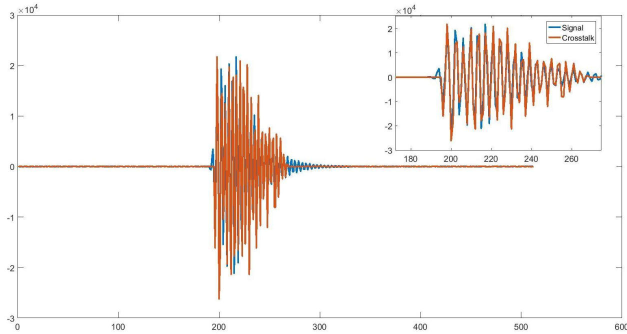

Figure 10: Crosstalk compensation.

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