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Upgrade of Beam Position Diagnostics System at FELiChEM *

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Abstract

FELiChEM is a user facility dedicated to energy chemistry research, developed at University of Science and Technology of China in Hefei. The beam position diagnostics system at FELiChEM has recently been upgraded. The facility typically operates in a special mode: macro-pulses at 1 Hz repetition rate with microsecond duration, each containing micro-pluses at a 59.5 MHz repetition rate. Both repetition rates are adjustable. The key advancement of beam position diagnostics system lies in the upgraded which now achieves the measurement of micro-pulse position. This enhancement enables real-time measurement of transverse position deviations for individual micro-pluses, providing essential diagnostics for investigating intra-macro-pulse instabilities. Post-upgrade characterization demonstrates a transverse position resolution better than 20 µm, satisfying design specifications. The upgraded system has been successfully integrated into routine operations. This paper will give a brief introduce of the machine, the hardware and software structure of the new micro-pulse position measurement system, and its performance in machine commissioning and operation.

INTRODUCTION

Free Electron Laser for Innovation Center of Energy Chemistry (FELiChEM) is a user-dedicated facility for energy chemistry research, capable of delivering infrared laser beams in both mid-infrared and far-infrared spectral ranges. The facility's electron gun can generate electron macro-pulses with a maximum duration of approximately 10 µs, each consisting of a train of micro-pulses with a pulse width of about 1 ns and selectable repetition rates of 238, 119, 59.5, or 29.75 MHz [1, 2]. Within the same pulse train, micro-pulses may exhibit positional, phase, and energy discrepancies due to various factors. If the micro-pulse discrepancies are not actively compensated, they will directly degrade the optimal lasing efficiency. However, the previous beam diagnostics system cannot provide micro-pulse-level measurement results, failing to provide effective data support for beam operators during operation. Therefore, during the upgrade, the upgrade of the beam position diagnostics system incorporated micro-pulse-level diagnostic capabilities, with a position measurement resolution better than 20 µm.

HARDWARE

The hardware of the new beam position diagnostics system consists of a signal processor, a front-end signal processing module, and a frequency synthesizer. The block diagram is shown in Fig. 1.

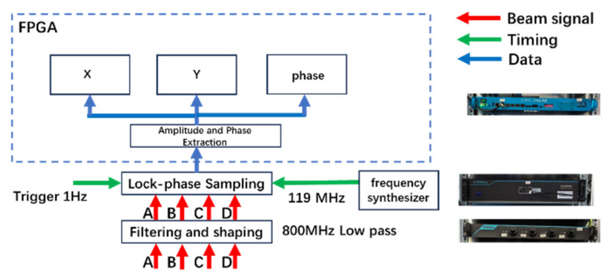

Figure 1: Block diagram of beam position diagnostics system.

The electronics parameters of the new beam position diagnostics system are listed in Table 1.

Table 1: The Electronics Parameters

Parameter	Value
Bandwidth	DC~800MHz
ADC bits	14
MAX ADC rate	1 GSPS
FPGA	xczu15eg
Clock	Ext.@119 MHz
Trigger	Ext.

The frequency synthesizer provides a 119 MHz reference clock to the system, which is phase-locked with the beam signal. Additionally, the frequency synthesizer can programmatically adjust the clock phase, ensuring that the sampling points of the measurement system align precisely with the designated positions. The front-end signal processing module is responsible for filtering and shaping, optimizing the beam signal waveform for accurate measurement. The signal processor consists of an ADC module and an FPGA. The ADC module receives the reference clock from the frequency synthesizer and generates a 952 MHz sampling clock using its internal clock chip. The ADC then digitizes the analog signal at a 952 MSPS rate and inputs the digital signal into the FPGA. The FPGA processes the sampled signals to calculate the micro-pulse position data.

The layout of the beam diagnostic system for the FELiChEM is shown in the left panel of Fig. 2. The entire setup employs 10 sets of button probes for beam position measurement. The right panel of Fig. 2 shows the actual hardware configuration, including the signal processor, frequency synthesizer, and the front-end signal processing module.

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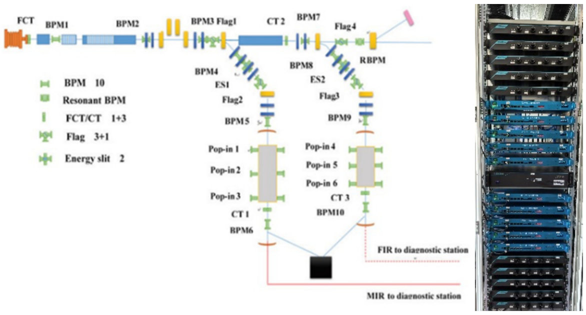

Figure 2: left: Layout of the beam diagnostic system, right: Pictures of cabinet.

ALGORITHM

The zero-crossing detection method and the lookup table method are bunch-by-bunch position measurement techniques based on phase-locked sampling [3–5]. These methods are originally developed for beam measurements in storage rings, but its application has also been successfully validated in single-pass accelerators.

In the new diagnostic system, the amplitude-phase extraction algorithm is based on two-point sampling. As shown in Fig. 3, the signal schematic uses circles to represent sampling points, with the solid circles selected for amplitude and phase calculation. The solid line in Fig. 3 connects the two sampling points, and the star represents the zero-crossing point. It can be observed that the beam signal is approximately linear near the zero-crossing point. Therefore, the sum of the two sampled values is used to represent the signal amplitude, while the difference between the two sampled values after linear operation is used to represent the signal phase.

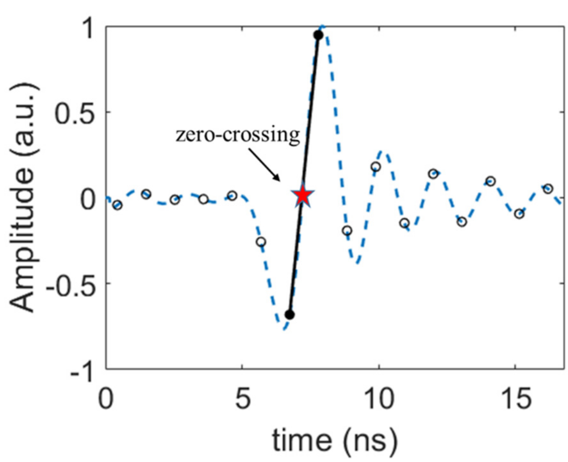

Figure 3: The signal schematic.

The sum of the amplitudes of the four channels represents the micro-pulse charge. The result of the four-channel amplitude difference ratio corresponds to the transverse relative position of the micro-pulse. the average phase of the four channels represents the micro-pulse phase. The transverse position of the macro-pulse can be calculated by charge-weighted averaging.

SOFTWARE

The signal processor embedded EPICS IOCs, running Linux operation system. FPGA and ARM exchange data via AXI bus. In the new beam position diagnostic system, the upper-level software interface has been redesigned. The previous system could only display the transverse position data of macro-pulses. After the system upgrade, the upper-level software interface can now display the three-dimensional position data of micro-pulses, the transverse position of macro-pulses, and the transverse distribution of micro-pulses within each macro-pulse. The upper-level interface of the new beam diagnostic system is shown in Fig. 4 and Fig. 5. The upper-level interface of a single BPM shows ADC raw data, Micro-pulse parameters and Macro-pulse parameters. The upper-level interface of the overview of BPM system shows transverse position of the macro-pulse and the transverse distribution of micro-pulses within each macro-pulse.

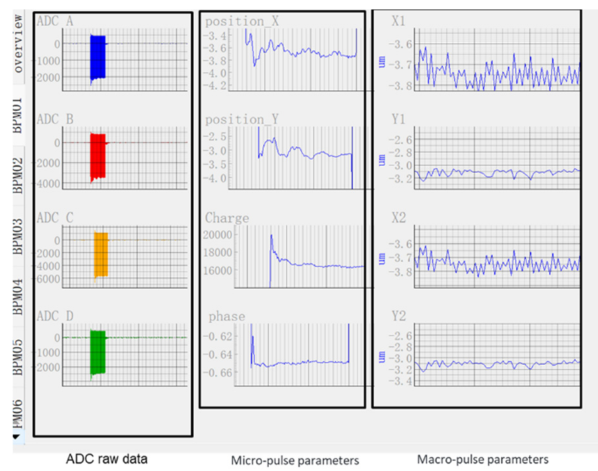

Figure 4: The upper-level interface of a single BPM.

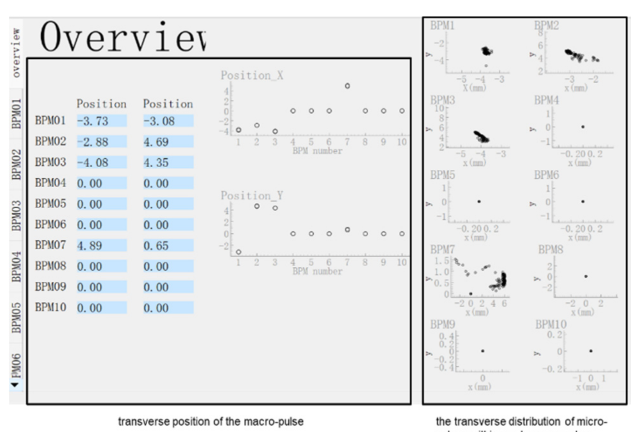

Figure 5: The upper-level interface of the overview of BPM system.

PERFORMANCE

After the new beam position diagnostic system was put into operation, EPICS was used to continuously

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accumulate data. By analyzing these historical data, the resolution of the system was calculated. This paper mainly evaluates the micro-pulse transverse position measurement resolution of the system. The resolution is evaluated using both noise analysis and PCA methods.

Uncertainty Analysis

Take multiple sets of data over the same period of time, calculate the difference between each micro-pulse's transverse position and the average value, and the result is the measurement uncertainty of the micro-pulse. The distribution of micro-pulse uncertainty is shown in Fig. 6. From the Fig. 6, it can be observed that the points with larger measurement uncertainty are primarily concentrated at the head of the pulse train. The standard deviation (STD) of the measurement uncertainty for #1 micro-pulses was calculated to determine the resolution of the measurement system, as shown in Fig. 7. As shown in Fig. 7, the horizontal measurement resolution is 8 μm, while the vertical measurement resolution is 15 μm. The measurement resolution is less than 20 μm, meeting the resolution requirements for the upgrade.

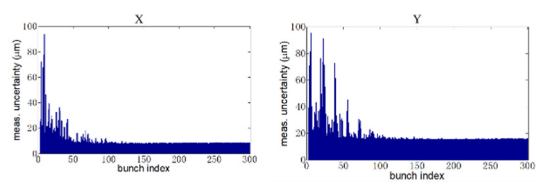

Figure 6: The distribution of micro-pulse uncertainty.

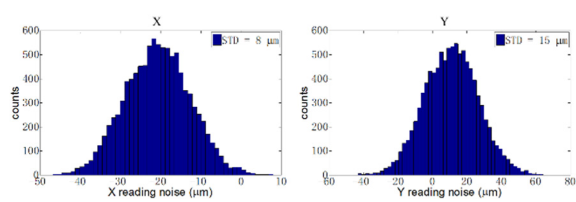

Figure 7: statistical histogram of measurement uncertainty

PCA

Multiple sets of data from the same time period were taken, and Principal Component Analysis (PCA) was applied to decompose the transverse position data [6]. The singular value distribution after SVD is shown in Fig. 8.

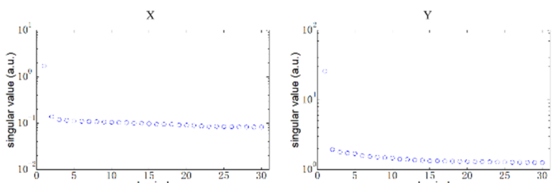

Figure 8: The singular value distribution after SVD

The first mode characterizes the transverse position. After setting this mode to zero, the measurement resolution of the transverse position was evaluated, as shown in Fig. 9. As shown in Fig. 9, the horizontal measurement resolution is 8 μm, while the vertical measurement resolution is 15 μm. The measurement resolution is less than 20 μm, meeting the resolution requirements for the upgrade.

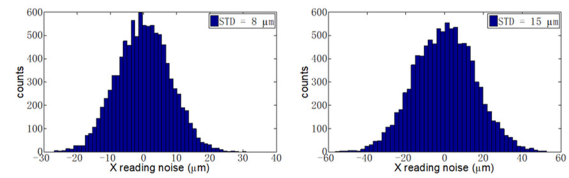

Figure 9: Noise statistical histogram.

The results of the two resolution evaluation methods were consistent, thereby mutually validating each other. Therefore, the horizontal measurement resolution is 8 μm, while the vertical measurement resolution is 15 μm.

CONCLUSION

The FELiChEM has completed the upgrade of its beam position diagnostic system. The system is now capable of three-dimensional position measurements of micro-pulses, transverse position measurements of macro-pulses, and transverse distribution measurements of micro-pulses. Through performance evaluation using noise analysis and the PCA method, the measurement resolution is determined to be 8 μm for the horizontal position and 15 μm for the vertical position, both surpassing the 20 μm requirement and meeting the upgrade objectives.

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