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MEASUREMENT OF BEAM PHASE AND ENERGY USING BPMs AND FCTs AT THE MEBT SECTION OF CSNS H⁻ LINAC

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Abstract

Accurately measuring the beam phase is critical when determining the ideal RF cavity parameters for beam acceleration. In the past, only Fast Current Transformers (FCTs) were used to measure the beam phase. However, with the upcoming upgrade of the MEBT section for the CSNS-II project, shorted strapline-type Beam Position Monitors (BPMs) will now be utilized to measure beam position, phase, and energy. LIBERA singlepass electron-ics are employed to measure the beam position and phase from the BPMs. Pairs of BPMs were used to measure beam phase shift, which can also be used to calculate beam energy. This paper compares beam phase meas-urement systematically by BPMs and FCTs.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is a platform for scientific research, consisting of an RF ion source, a 3 MeV Radio Frequency Quadruple (RFQ), 80 MeV Drift Tube Linac (DTL), 1.6 GeV Rapid-Cycling Synchrotron (RCS), and several beamlines. Significant upgrades will be made to the Medium Energy Beam Transport (MEBT) for the future CSNS-II as part of a power upgrade. The MEBT section consists of 5 Fast Current Transformers (FCT) [1] and 7 Beam Position Monitors (BPM). With the upgrades planned for the second phase, the functionality of the existing FCTs will be replaced by a BPM system. Therefore, a comparative study of FCT and BPM systems for phase and energy measurements in the CSNS-II MEBT are necessary, including system calibration, consistency in phase and energy measurements, and comparison of phase stability and reliability in first and second harmonics.

The BPM system will use Libera SPH [2], an electronics device designed for beam position and phase measurement in particle accelerators and beamlines, and the FCT system has been using self-developed electronics on CSNS for about ten years. This study mainly compares two sets of closely located beam position monitors (BPM05 and BPM07) and fast current transformers (FCT03 and FCT05) in the MEBT section. Figure 1 shows the beam instruments layout of the CSNS MEBT.

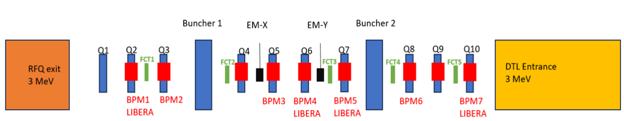

Figure 1: Layout of the CSNS MEBT.

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CABLE OFFSET MEASUREMENT OF BPM SYSTEM

Factors affecting the accuracy of accelerator beam phase measurement are detector performance, cable delay, electronics discrepancies, and other factors. The transmission of beam signals is influenced by cable delays, leading to measurement deviations. Therefore, accurate calibration and compensating cable delays are necessary to ensure measurement accuracy. Discrepancies between electronic modules, such as signal processing speed and response time, can result in inconsistent measurement results. Calibration and adjustment of electronic differences are required to ensure measurement consistency. Other factors affecting the accurate measurement of the accelerator beam phase include environmental conditions, such as temperature and humidity.

Considering these factors, accurate measurement of the accelerator beam phase requires a comprehensive assessment of detector performance, cable delay, electronics discrepancies, and other factors [3]. Effective control and calibration of these factors during the measurement process are essential to ensure the accuracy and reliability of measurement results.

Since all detectors have been installed on the accelerator beamline, calibration measurement was only performed on the FCTs in the past phase, with no calibration done for the BPM. Additionally, the differences between electronic channels are minimal. Therefore, calibration is only carried out on the BPM cables in this study. The cables between the probes and electronics of each system use LMR200 at both ends and LMR400 in the middle. The goal was to investigate phase consistency and synchronization using two different measurement methods.

The first method involved utilizing a Vector Network Analyzer (VNA) to perform Time Domain Reflectometry (TDR) measurements on the cables connecting the BPM05/BPM07 shown in Fig. 2. The TDR plots generated by the VNA are analyzed to determine the cable lengths and calculate the phase offset. From Table 1, it can be observed that the lengths of the electronic cables are all around 37.9 meters, with minimal differences.

Table 1: BPM Cable Length Measurement

Cable Length	A [m]	B [m]	C [m]	D [m]
BPM05	37.81	37.93	37.93	37.93
BPM07	37.87	37.83	37.88	37.87

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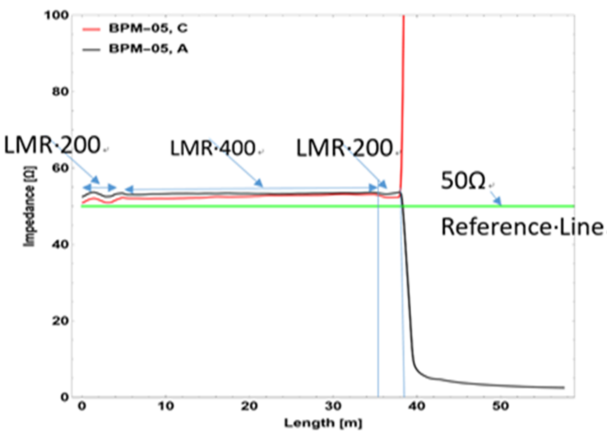

Figure 2: Cable length measurement using Time Domain Reflectometry (TDR) method.

The second method employed an oscilloscope in conjunction with a function generator to measure the signal delay along the cables connecting the beam position monitors and current transformers, allowing for the calculation of phase offsets, as shown in Fig. 3 and Fig. 4. by comparing the input and output signals on the oscilloscope, we were able to determine the phase offsets based on the time differences.

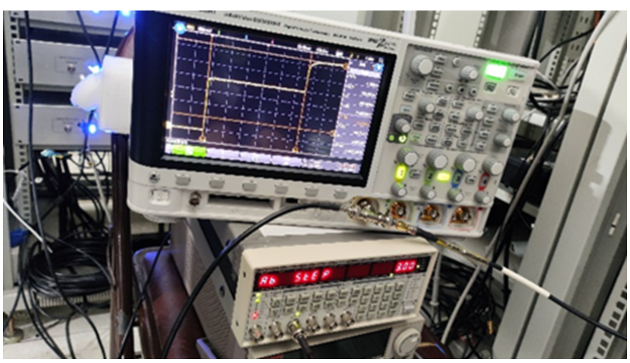

Figure 3: Measure cable delay using an oscilloscope with a function generator.

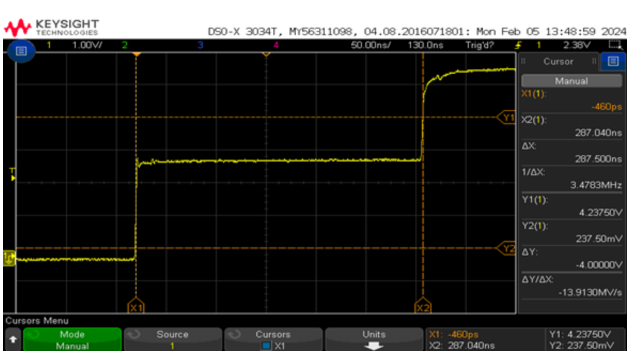

Figure 4: Measure cable delay using an oscilloscope with a function generator.

As shown in Table 2, the delay of the two sets of cables is approximately 144 ns, significantly smaller than the RF pulse width of 3 ns.

Table 2: The Cable Delays of the Two BPMs

Probe (line NO.)	A [ns]	B [ns]	C [ns]	D [ns]
BPM05 (1020)	144.14	144.92	144.92	144.92
BPM07 (1022)	144.92	144.92	144.92	144.92

Through these two measurement methods, we assessed the phase consistency and synchronization of BPMs, and all BPM cable delays have high consistency. Compared to the difference in cable delay, the influence of the probe end and electronic end can be ignored.

PHASE SCAN

The influence of beam position on beam phase is mainly due to two factors if we use the BPM measuring phase: (1) BPM inter-electrode coupling and (2) the longitudinal component of the electromagnetic field generated by the non-relativistic beam. So, the phase of the vector sum of the four electrode signals should be adopted to measure the beam phase precisely with BPMs.

Measuring the accelerator beam phase ensures particle accelerators' proper operation and performance. Accurate beam phase measurements significantly control and optimize the accelerator system's beam trajectory, timing, and synchronization.

Two methods are used to measure the accelerator beam phase: BPM and FCT. BPMs are commonly used devices that detect the beam position in the accelerator. The beam's phase can be determined by analysing the signals, and FCTs measure the beam current, which is directly related to the beam phase. In order to verify the stability and accuracy of BPMs in phase measurement and ensure that the system can reliably measure phase information under different conditions for replacing FCTs, tests were conducted on the phase response of BPM05, 07 and FCT03, 05 in the buncher-01 scanning phase, as shown in Fig. 5.

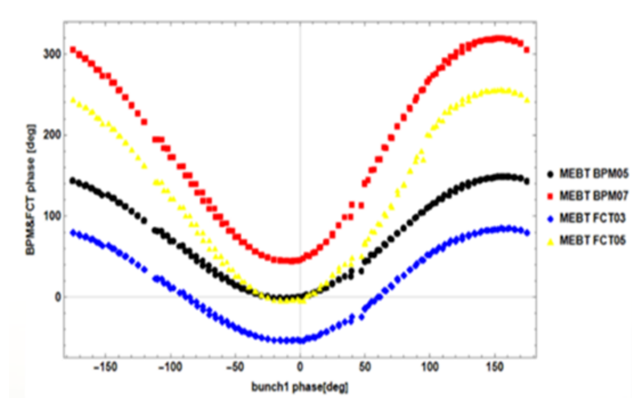

Figure 5: BPM and FCT phase measurements performance in buncher cavity phase scanning.

Using the fundamental or second harmonic signal for calculating beam phase depends on the specific requirements of the measurement, considering factors such as sensitivity, pre-

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cision, noise tolerance, and calibration complexity. While the second harmonic signal offers advantages in sensitivity and resolution, it may introduce noise sensitivity and calibration challenges. The fundamental signal, on the other hand, is more straightforward to use but may have limitations in sensitivity and precision. Figures 6 and 7 show that both the fundamental and second harmonic signals effectively reflect the phase information of the beam.

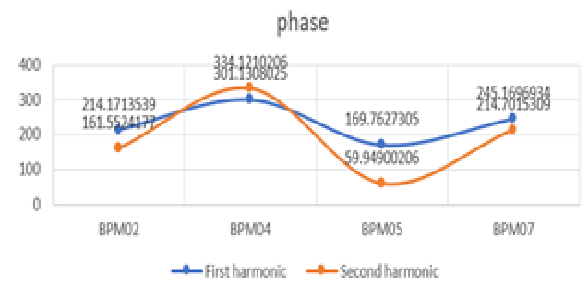

Figure 6: The average values of the fundamental and second harmonic signals from 78 data points of four BPMs.

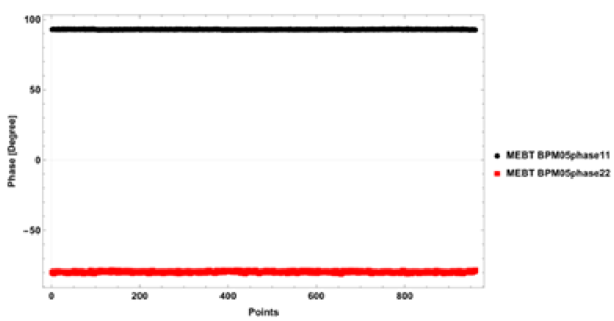

Figure 7: Stability testing of phase information from approximately 1000 fundamental and second harmonic BPM signals.

JITTER OF PHASE WITHIN A MACRO-BUNCH

Since signal phases can be measured once per microsecond, beam phase jitter within a macro-bunch was investigated. The result is shown in Fig. 8.

Table 3: Impact of Beam Chopping on Accelerator Beam Phase Measurements

Probe	WO-Chopping	W-Chopping	△
BPM01	160.63° ± 0.10	161.04° ± 0.08	0.25 %
BPM04	92.02° ± 0.14	92.25° ± 0.10	3.3 %
BPM05	222.14° ± 0.16	226.23° ± 0.19	1.8 %
BPM07	147.68° ± 0.40	149.53° ± 0.25	1.2 %
FCT03	158.45° ± 0.15	153.9° ± 0.12	2.9 %
FCT05	42.18° ± 0.24	39.05° ± 0.35	7.9 %

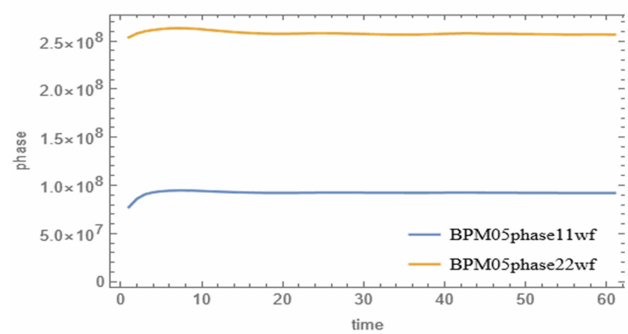

Figure 8: The phase stability of the second harmonic relative to the fundamental within a macro-pulse is relatively stable; BPM05 phase11-wf means the fundamental, and BPM05 phase22-wf means the second harmonic.

Table 4: Energy Measurement of BPM and FCT Using the Time of Flight Method

Probe	FCT	BPM
Location	3 and 5	5 and 7
D [m]	0.85378	0.896
N	11	12
Phase [°]	42.98 and 156.81	91.24 and 160.25
T [ns]	3.086	3.086
Offset [°]	178.566 and -140.946	144.92 and 144.92
Energy [MeV]	3.093	2.988

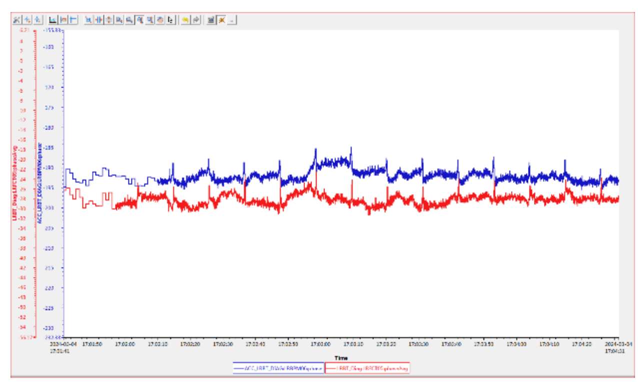

Figure 9: Consistency performance of accelerator energy measured by BPM and FCT during operation at 25 Hz.

When conducting phase measurements on multiple BPMs and FCTs, we observed a high level of consistency in the phase measurements obtained from the BPMs before and after the beam was chopped. Specifically, the beam state without chopping was 100 µs-13 mA, while the beam state when chopped was 100 µs-7.8 mA, as shown in Table 3.

ENERGY MEASUREMENT

Time of Flight (TOF) is a commonly used method for measuring accelerator energy [4]. The principle behind TOF is based on measuring the time taken for particles to travel a known distance. By knowing the distance and the

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time of flight, the velocity of the particles can be calculated using the formula:

$$v = \frac{D}{NT + \triangle t}, \tag{1}$$

Once the velocity of the particles is determined, their energy can be calculated.

Data from both BPMs and FCTs were analyzed to calculate the energy of the accelerator beam using the time-of-flight method. The distance between MEBT' BPM05 and MEBT' BPM07 is 0.893 m, and the phase offset caused by cable length, probe processing technology, and electronics can be summarized as line length offset. According to the measurement results, two BPMs lines with equal length can have equal offsets. The distance between MEBT-FCT03 and MEBT-FCT05 is 0.89537 m, and their calibration phase offsets, which are in CSNS, are -140.94° and -178,56°. As shown in Table 4, using all data obtained, two detectors calculated comparable energy values, and Figure 9 demonstrates the consistency and long-term stability in calculating accelerator energy using FCT and BPM.

CONCLUSION

This paper compares phase measurement and energy measurement between FCT and BPM. The phase measurement includes phase scanning using a buncher cavity, phase jitter within macro pulses, and the difference in beam phase before and after beam chopping. The results indicate that BPM has excellent phase and energy measurement capabilities.

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