ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUAO01

PRECISE BUNCH CHARGE MEASUREMENT USING BPM PICKUP*

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Abstract

Precise bunch charge measurement is the fundamental of charge feedback, beam lifetime measurement, beam loss monitor, as well as the basis of the related interlocking work. Beam position monitor (BPM) is often used for high-resolution bunch charge measurement due to its superior performance. In this paper, the pros and cons of Stripline BPM, Button BPM, and Cavity BPM for measurement of bunch charge in storage ring and FEL will be discussed. The related simulations and beam experiment results are also mentioned, the results show that the relative bunch charge resolution of the Button BPM can reach 0.2‰ in SSRF, 0.73‰ and 0.21‰ of the SBPM and CBPM in SXFEL, respectively. Besides, based on the method of beam experiments, we systematically studied the position dependence of BPM pickup for bunch charge measurement and related compensation algorithms.

INTRODUCTION

Shanghai Synchrotron Radiation Facility (SSRF) is a low emittance 3rd-generation light source consisting of a 3.5 GeV storage ring, a full energy booster and a 150 MeV linac, as well as dozens of beam lines and experimental stations. The Shanghai soft X-ray free electron laser (SXFEL) is a test facility for exploring key FEL schemes (EEHG/HGHG) and technologies, which adopt FEL frequency doubling of ultraviolet band seeded laser of 265 nm to achieve output wavelength of 9 nm, 100 fs pulse duration, 10 HZ repetition rate, and 100 MW peak power[1]. The overall length of SXFEL is about 300 meters and the nominal electron beam energy of the linac is 0.84 GeV. And it will be upgrade to a user facility in 2021. In addition, SHINE, a hard X-ray FEL facility with high energy, high repetition rate, is also under pre-research. The total length of the SHINE is about 3.1 Km，located near SSRF and SXFEL, the goal is to build a superconducting linear accelerator with an energy of 8 GeV, 3 undulator lines, 3 light speed lines, and the first batch of 10 experimental stations. Together with SSRF and SXFEL to build a photonic science center in China.

For high quality electron beams, accurate measurement of beam charge and its stability is one of the most important parameters for stable operation of accelerator. For example, for SHINE, so as to avoid damage the cryogenic superconducting undulator caused by beam loss, a requirement that the beam loss measurement accuracy is better than 0.01% in key areas is proposed. Therefore, research on this topic has great significance to the efficient operation of these facilities.

BPM picks up the electromagnetic field excited when the bunch passes through the vacuum chamber, which carries the information of the bunch, which is widely used in the measurement of a variety of bunch parameters. Its unique characteristics are also one of the methods to achieve high-precision bunch charge measurement.

This paper focuses on the motivation of using BPM probes for high-precision bunch charge measurement, introduces the principle of BPM for bunch charge measurement. The dependence of the horizontal and vertical parameters for high-precision bunch charge measurement is simulated, and some simulation results are verified by beam experiments. In addition, the system signal conditioning and data acquisition schemes and digital signal processing algorithms are also mentioned.

MEASUREMENT PRINCIPLE

For the electrostatic induction BPM, when the beam passes through the vacuum chamber, the electrode generates an induced charge under the action of electrostatic induction, and the induced signal contains the position and charge amount information of the bunch. In electron accelerators, typical probes are SBPM and Button BPM. The output signal can be expressed by Eq.(1) and (2), respectively.

$$V(t)=\frac{\phi Z}{4\pi}\left[e^{-\frac{t^2}{2\sigma^2}}-e^{-\frac{(t-\frac{2l}{c})^2}{2\sigma^2}}\right]\cdot\frac{Q}{\sqrt{2\pi}\sigma}\cdot \quad (1)$$

$$V_B(t)=\frac{Q}{2\pi^{\frac{3}{2}}}\cdot\frac{\varphi lR}{\beta_b c}\cdot\frac{t}{\sigma_t^{\ 3}}\cdot e^{-\frac{t^2}{2\sigma_t^{\ 2}}}. \quad (2)$$

For Cavity BPM, when the bunch passes through the cavity, various characteristic modes of the electromagnetic field will be excited due to the tail field effect. For a standard cylindrical cavity, the excited TM_{010} mode which contains the bunch charge message can be represented by Eq. (3) :

$$V_p^{\ 010}=\frac{q\omega_{010}}{2}\cdot\sqrt{\frac{Z}{Q_{ext}^{\ \ 010}}\cdot\frac{2LT^2}{\varepsilon\omega_{010}\pi a^2 J_1^{\ 2}(\chi_{01})}}\cdot \quad (3)$$

$$J_0^{\ 2}(\frac{\chi_{01}}{a}\rho)\cdot e^{-\frac{t}{\tau_{010}}}\cdot e^{-\frac{\omega_{010}\sigma_z^{\ 2}}{2c^2}}\cdot\sin(\omega_{010}t+\varphi)$$

It can be seen from the above expression that the BPM pickups for bunch charge measurement still has the dependent factors such as bunch length, position offset, etc.

*Work supported by National Natural Science Foundation of China (2016YFA0401903) and Ten Thousand Talent Program and Chinese Academy of Sciences Key Technology Talent Program
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ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUAO01

Therefore, in order to accurately measure the bunch charge, the dependence of transverse and longitudinal parameters needs to be studied.

SIMULATION

In order to simulate the influence of the horizontal and vertical parameter dependence on BPM for charge measurement, CST（Computer Simulation Technology） was used to build the BPM probe model and simulate the relevant parameters.

Based on the SBPM structure and size parameters which used in SXFEL, a simulation model is established by CST, as shown in Fig. 1. The electrode length was designed at 150mm, and the corresponding frequency is 500 MHz and its integer multiples. To reduce the crosstalk between the electrodes, the electrode opening angle was designed at 30° and the vacuum tube diameter is 25mm.

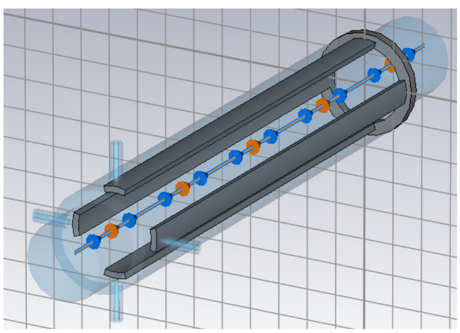

Figure 1: CST model of the SBPM.

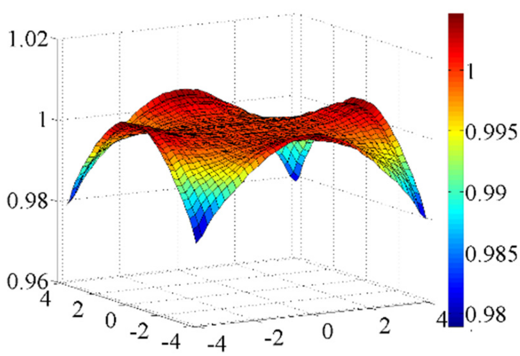

Figure 2: Simulation results of the SBPM @ 10 ps bunch length.

Figure 2 shows the dependence of the electrode and signal simulated by CST on the position of the bunch when the bunch length is 10ps. The simulation results show that in the case of position offset (1mm, 1mm), the deviation of the electrode sum signal relative to (0mm, 0mm) is about 0.01%.

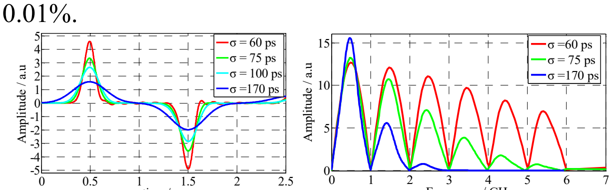

Figure 3: The relationship between SBPM electrode output signal and bunch length.

Figure 3 shows the time-domain waveform and frequency spectrum of the SBPM electrode signal simulated by CST under different bunch lengths.

The results show that with the increase of the bunch length, the peak amplitude of the bipolar pulse gradually decreases, and the spectrum energy gradually concentrates toward the low frequency.

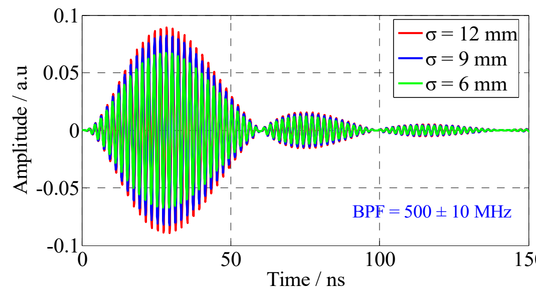

Figure 4: Waveforms after narrowband filtering under different bunch lengths.

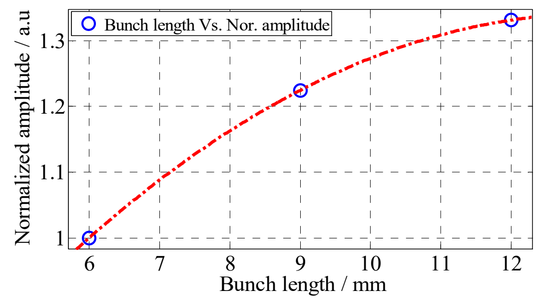

Figure 5: Dependence of SBPM signal and bunch length.

A 500±10MHz narrow-band digital filter on the simulated waveforms with different bunch lengths. The filtered waveforms are shown in Fig. 4. The signal amplitude is extracted to verify the dependence of SBPM on bunch charge measurement and bunch length, As shown in Fig. 5. Base on the results, the output signal changes about 4% when the bunch length changes 0.5ps around 2ps was estimated

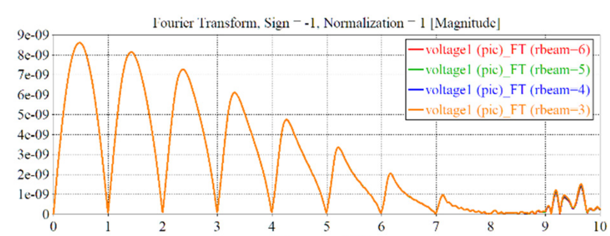

Figure 6: Dependence of SBPM signal and cross-sectional size.

Similarly, a simple simulation of the dependence of the cross-sectional size of the bunch has been done, as shown in Fig. 6. The simulation results show that when the operating frequency < 10 GHz, the impact of the cross-sectional size on the measurement of the bunch charge is negligible.

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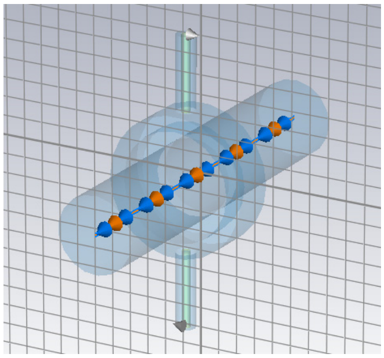

Figure 7: CST model of the Cavity BPM (TM_{010}).

For the cavity BPM with TM_{010} mode as the main mode, is often used in the FEL device for the relative measurement of the bunch charge and the beam arriving time measurement. Therefore, in accordance with the existing CBPM parameters of SXFEL, a model was established in CST to simulate the bunch position dependence and bunch length dependence, as shown in Fig. 7.

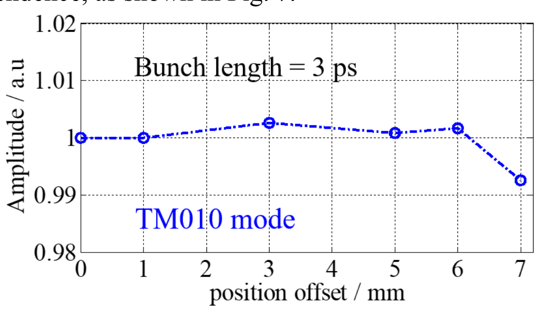

Figure 8: Position dependence of TM_{010} cavity.

Figure 8 shows the dependence of the TM_{010} mode signal simulated by CST on the position of the bunch when the bunch length is 3ps. The simulation results show that in the case of position offset < 6 mm, the deviation of the signal is less than 0.1%.

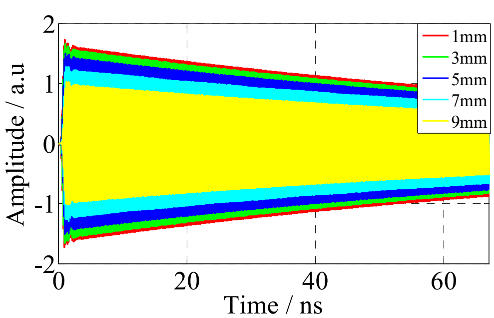

Figure 9: Bunch length dependence of TM_{010} cavity.

Figure 9 shows the time-domain waveform after digital filter of the TM010 mode signal simulated by CST under different bunch lengths. The dependence of TM_{010} mode signal and bunch length was shown in Fig. 10, the results are in good agreement with the theoretical formula.

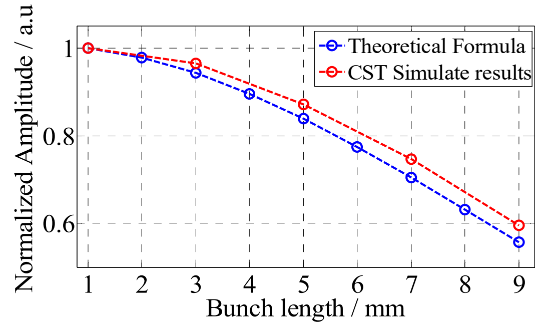

Figure 10: Dependence of TM_{010} mode signal and bunch length.

BEAM EXPERIMENT

Based on the modeling and simulation of CST, the relationship between the beam position dependence and the bunch length dependence of the BPM pickups were obtained. On this basis, we did some experiments in SSRF and SXFEL for preliminary verification.

In the laboratory, we used the method of pulling a copper beryllium wire through the SBPM and scan the two-dimensional position to verify the relationship between the electrode sum signal and the position. The experimental platform is shown in Fig. 11, and the scanning results are shown in Fig. 12. The qualitative results are consistent with the simulation results.

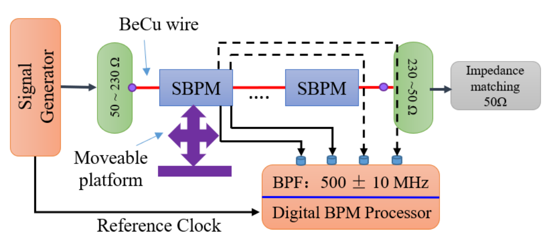

Figure 11: Diagram of the experiment platform.

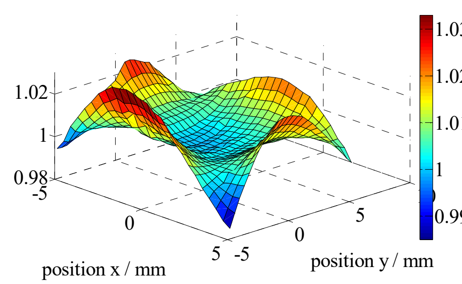

Figure 12: Dependence between electrode sum signal and position.

During the injection transient of SSRF, the beam position oscillation process can be used to analyze the relationship between the bunch charge and the position dependence. As shown in Fig. 13, under ± 0.4mm position oscillation, the bunch charge depends on the measurement position. The slope is about 0.0005 / mm.

9th Int. Beam Instrum. Conf. IBIC2020, Santos, Brazil JACoW Publishing
ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUA001

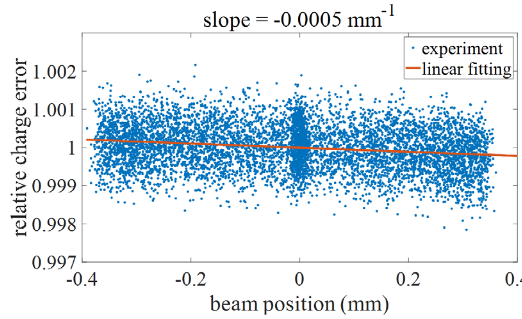

Figure 13: Dependence between electrode sum signal and bunch position.

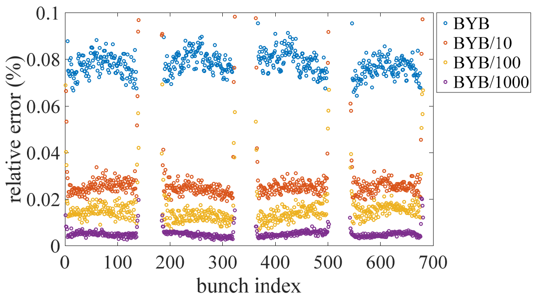

Figure 14: Resolution of bunch-by-bunch charge measurement.

In SSRF, the relative bunch charge of bunch-by-bunch is measured, and the relative uncertainly under different data refresh rates are obtained by data averaging, as shown in Fig. 14. Compared with the closed orbit measurement, the beam position stability is on the order of micrometers (< 2 μm), and the relative charge measurement error is about 1E-6 based on the position-dependent slope. For Turn-by-Turn beam position measurement, with 10 times σ (~20 μm) to evaluation, the relative charge measurement error is about 1E-5. Therefore, for the synchrotron radiation source, under normal operating conditions, the error introduced by the position dependence is basically negligible. Apart from this, assuming that the beam life time is 10 hours, the amount of charge in 1 second is reduced by 3E-5, so the beam life time can be measured in the order of 10s or minutes.

Regarding the beam position dependence of cavity of TM_{010} mode, two adjacent reference cavities of CBPM are used in the SXFEL for experiments. The experimental platform is shown in Fig. 15. The first Cavity is fixed as a reference, and a moving platform is used to move the adjacent cavity to simulate the beam offset.

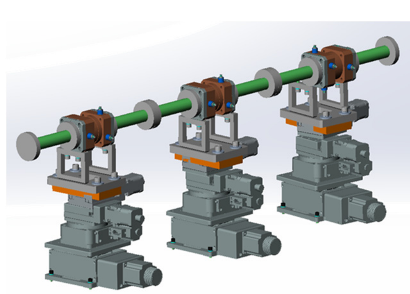

Figure 15: Experimental platform setup in SXFEL.

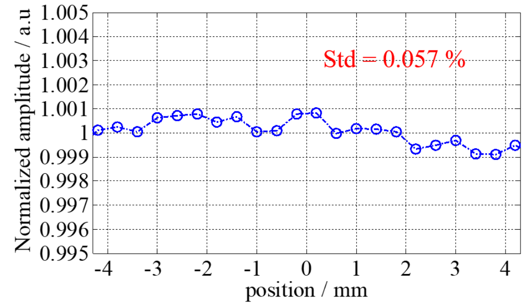

Figure 16: Results of position dependence of the TM_{010} cavity.

Due to the limitation of the movable platform, the moving range can only be moved within ±4.2mm. According to the experimental results, within the range of ±4.2mm, the reference cavity position dependence is not obvious, which is consistent with the CST simulation results, as shown in Fig. 16, and the relative amplitude extraction difference at different positions is better than 0.1%.

SIGNAL PROCESSING METHOD

Since the bipolar pulse signal output by the SBPM electrode is a wideband signal, there are two processing solutions for the signal conditioning and signal acquisition of the SBPM system, broadband and narrowband.

According to the results of simulation analysis, when the SNR the output signal of the pickups higher than the effective bit of the ADC under a large bunch of charges, a narrow-band filtering scheme is used to broaden the waveform, so as to obtain more processing gain. In the choice of system internal / external clock or internal / external trigger, a test system was setup in SXFEL for comparison. The experimental comparison results are shown in Fig 17. The results show that for SBPM / Button BPM, under the narrowband filtering scheme, the configuration of external clock and external trigger has limited improvement in resolution.

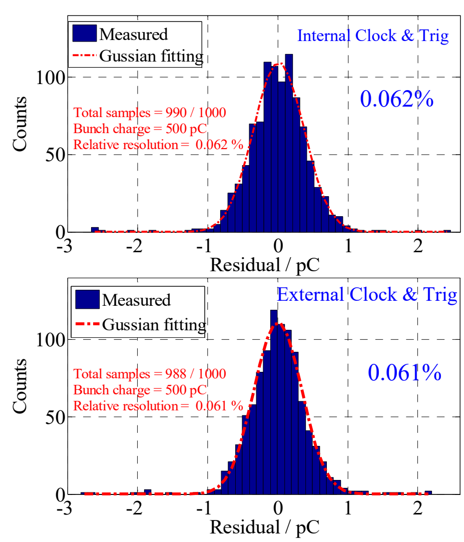

Figure 17: Relative error of the SBPM system by Internal Clock and Internal Trigger (Top). By External Clock and External Trigger (Bottom).

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On the other hand, for systems that require phase-locked sampling (for example, BPM in the storage ring is used to acquire bunch-by-bunch signals). In this case, the jitter of the sampling phase will seriously deteriorate the performance of the system. Based on this, we propose the Two-phase sampling based peak seeking method to minimize the impact of sampling phase jitter, so as to extract the peak-value accurately. The diagram is shown in Fig. 18, the phase of the two points sampled at the time can be derived from the ratio of the two points with a fixed delay, and the value of the peak point can be obtained from the ratio of the normalized curve[2 3].

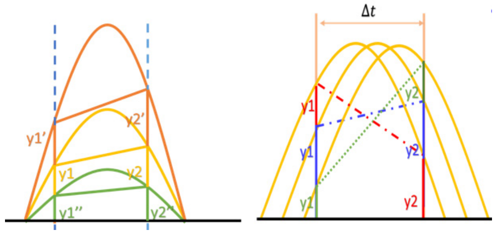

Figure 18: Diagram of method of two-phase sampling based peak seeking.

Based on this data acquisition scheme, it is applied in the SSRF bunch-by-bunch charge measurement. As shown in Fig. 19, it compares the std value of single-point peak extraction method and the two-phase sampling based peak seeking method to extract the peak. It can be seen that two-phase sampling based peak seeking method basically minimized the influence of sampling phase jitter. Under the average of more than 1W sets of data, the resolution of bunch charge measurement better than 0.02%, as shown in Fig. 20.

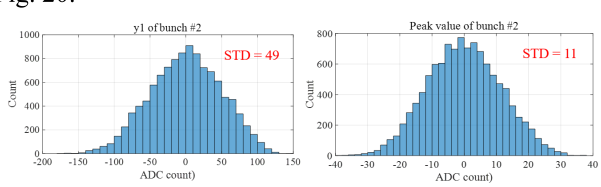

Figure 19: The std value of single-point peak extraction method (Left) and the two-phase sampling based peak seeking method (Right) to extract the peak.

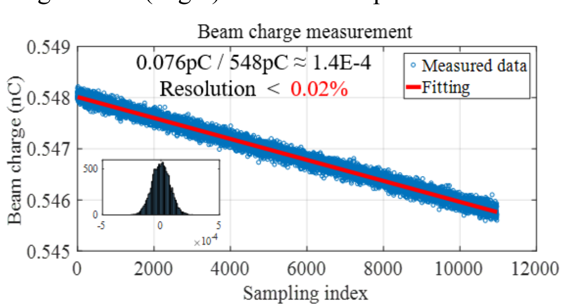

Figure 20: Resolution of bunch charge measurement.

For cavity pickup, it couples a narrowband signal. For low-Q cavity pickup, because the decay time is very small, the analog IQ demodulation to baseband is used to demodulate the amplitude and phase information of the signal. For high-Q cavity pickup, because the decay time is large, the ADC can collect more effective data points in the effective waveform section, so the method of down-conversion to low IF is often adopted. In digital signal processing, high-Q cavity signals have more processing methods [4]. To balance the signal processing gain and the relative signal to noise ratio, the data interception algorithm can improve the resolution of the system to a certain degree. Through simulation, when the signal processing length is about twice the decay time, the relative uncertainty of processing can reach the minimum value. The Cavity data on SXFEL is processed. When the data processing length is 2.18 times decay time, the relative uncertainty is reduced from 0.044% to 0.021%.

CONCLUSION

The BPM pickups has a high amplitude extraction accuracy due to its unique characteristics, so it is often used for accurate bunch charge measurement. The dependence of the horizontal and vertical parameters for high-precision bunch charge measurement is simulated, and some simulation results are verified by beam experiments. In addition, the system signal conditioning and data acquisition schemes and digital signal processing algorithms for SBPM / Button BPM and cavity BPM also are mentioned, which can minimize the uncertainly of measurement.

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