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BEAM CHARGE MEASUREMENT USING THE METHOD OF DOUBLE-CAVITY MIXING *

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Abstract

The measurement of beam charge is a fundamental requirement to all particle accelerators facility. In this paper, using the TM010 mode of the cavity BPM to measure the beam charge will be introduced. The data processing methods including harmonic analysis, time domain analysis and principle component analysis (PCA) are used and compared in evaluating the resolution of the beam charge. On the basis of this, the results of the evaluation at a ultra-low charge are also given and indicates the superiority of the cavity probe in the measurement of lower beam charge. In addition, the use of double-cavity mixing method to measure the beam charge will be proposed as well.

INTRODUCTION

Beam charge is a fundamental parameter for the particle accelerator facility; therefore, the beam current detector is a very important diagnostic means. There exist many methods such as various types of current transformers (CT), faraday cup (FC), etc.

In addition to that, using the sum signal of the beam position monitor (BPM) four electrodes and the TM010 mode of the cavity BPM can also to achieve the relative measurement of the beam charge. Using the reference cavity of the CBPM to measure the beam charge will be discussed in this paper. Based on this, the method of double cavity mixing to measure beam charge will be proposed and the result indicating that this method can achieve a higher beam charge resolution.

PRINCIPLE OF THE MEASURMENT

For a cylindrical pill-box cavity, when the beam source runs along the z-axis, the bunch does not lose energy in the transverse electric field of the TE mode. However, because of the longitudinal electric field of the TM mode, the bunch loses energy in the longitudinal electric field excited by itself and effectively induces the excitation mode. Therefore, only the TM modes are excited and the amplitude is determined by the bunch energy that is lost. Considering the asymmetric characteristics of TM110 dipole mode which has a strong linear dependencies to the beam offset and the beam charge, whereas TM010 monopole mode unaffected by the beam offset but it is proportional to the bunch charge and bunch length. Electric fields of the TM010 and TM110 mode are shown in Fig. 1.

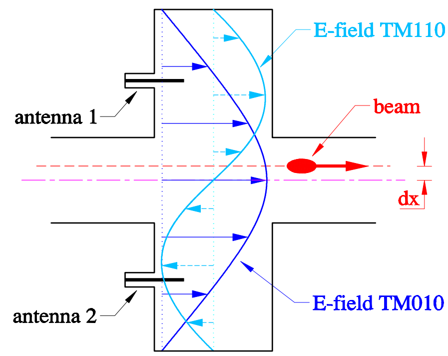

Figure 1: Electric fields of the TM010 and TM110 mode.

According to this characteristic, the beam charge can be measured using the TM010 mode of the cavity BPM. The TM010 mode signal coupled from the cavity can be expressed by Eq. (1):

$$V_{\mathrm{p}}^{010} = \frac{q\omega_{010}}{2} * \sqrt{\frac{Z}{Q_{ext}^{010}} * \frac{2LT^2}{\varepsilon\omega_{010}\pi a^2 J_1^{\,2}(\chi_{01})}} * J_0(\frac{\chi_{01}}{a}\rho) * e^{-\frac{t}{\tau_{010}}} * \sin(\omega_{010}t+\varphi) \quad (1)$$

where the q is the beam charge we want to get, J_1 is the first-order Bessel function of the first kind, ω_{010} is the resonant angular frequency of the TM010 mode, χ_{01} is the first root of $J_0(\rho) = 0$ and a is the cavity radius. Since $J_0(\frac{\chi_{01}}{a}\rho)$ is appropriately equal to 1 when ρ is small. Thus, when the beam deviates from the electric centre within a small range, the signal amplitude is independent of the beam offset but dependent on the beam charge and the beam length. If we assume that the beam length is constant during the measurement process, the coupled signal strength is related to the beam charge only and proportional to it [1].

MIXING WITH LOCAL OSCILLATOR

For the beam experiment in Dalian Coherent Light Source (DCLS) [2], the reference cavities of the cavity BPM are used to measure the beam charge. The system diagram is illustrated in Fig. 2.

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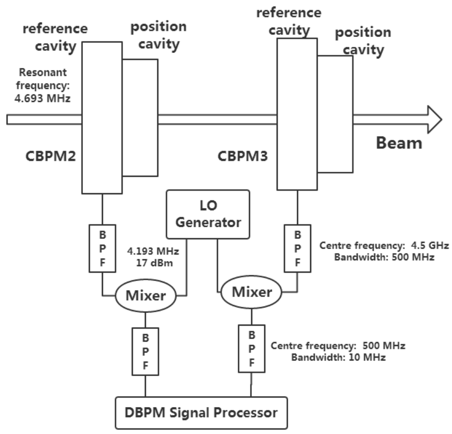

Figure 2: System diagram of using cavity BPM to measure the beam charge.

A sinusoidal signal of 4.193 GHz is generated by a local oscillator and mixed with the reference cavity signal. Since the amplitude of the LO signal is a constant value and irrespective of the beam charge, the amplitude of the signal after down-conversion is proportional to the beam charge.

To verify that the amplitude of the reference cavity signal is independent of the beam position, CBPM2 was fixed as a reference and moved CBPM3 by a stepping platform. Due to the limitation of the platform, the dynamic range was controlled within ±400 um. The relationship between the normalized amplitude and the beam position was shown in Fig. 3.

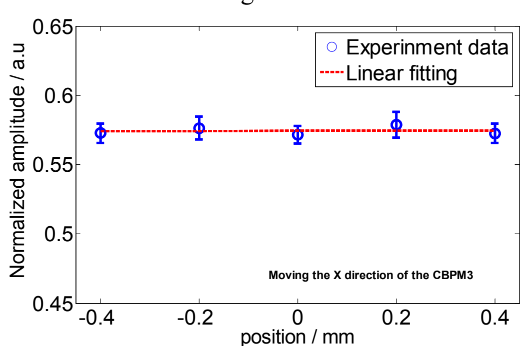

Figure 3: Dependence of the cavity signal amplitude (beam charge measurement) and the beam position.

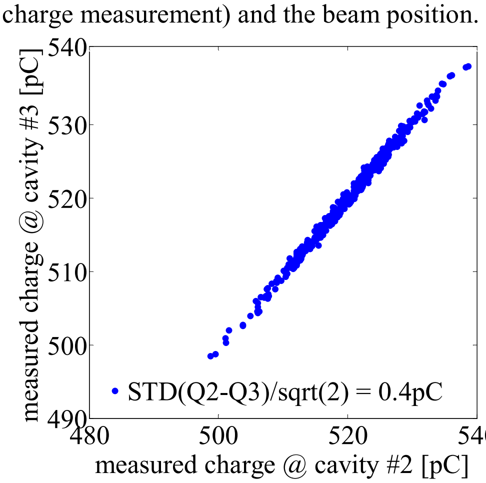

Figure 4: Evaluation results of beam charge resolution using cavity BPM2 and cavity BPM3.

Fig. 4 show the evaluation results of beam charge resolution using the cavity BPM2 and cavity BPM3 when the beam charge is about 500 pC. The relative resolution is about 0.08% using the method mixing with the LO signal, compared with the charge resolution about 1% for the ICT, which indicates the higher performance.

Change the charge of the beam so as to evaluate the relative resolution of the measuring system at different charge levels. For the data processing methods, different methods including Fast Fourier Transform (FFT), Hilbert transform and Principal Component Analysis (PCA) are be used to compare. The evaluation results are illustrated in Fig. 5.

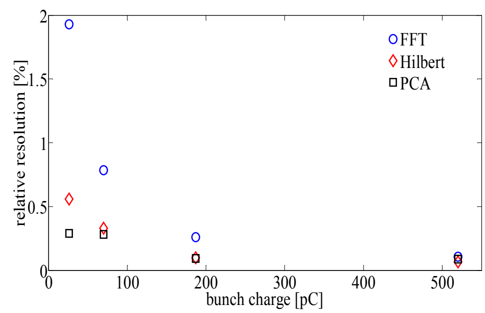

Figure 5: Comparison results of relative beam charge resolution using different data process methods.

The results show that the relative resolution results obtained by these three data processing methods are similar at higher charge levels but PCA method exhibits a superiority at a lower beam charge conditions.

To further verify that the CBPM can still work better in the ultra-low charge conditions, we designed an experiment scheme to obtain an ultra-low charge environment by extending into a profile. And the beam loss factor of 0.67 between CBPM6 and CBPM7 was measured. Predicting the Q7 value using the Q6 measured value combined with the K_{loss} to evaluate the resolution. Figs. 6, 7 and 8 show the results using the data processing method of FFT, Hilbert transform and PCA methods, respectively.

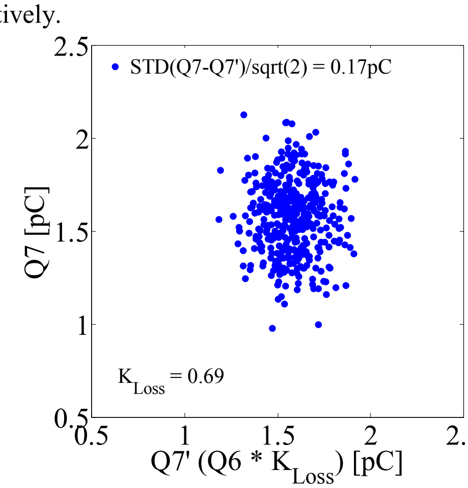

Figure 6: Evaluation of the resolution under ultra-low charge using the FFT method.

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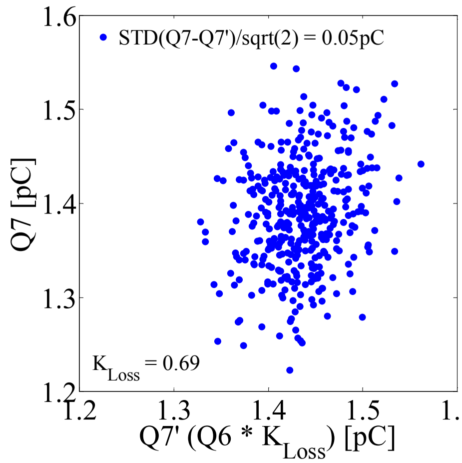

Figure 7: Evaluation of the resolution under ultra-low charge using the Hilbert transform method.

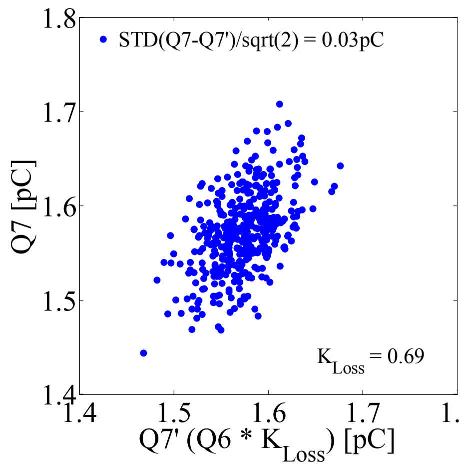

Figure 8: Evaluation of the resolution under ultra-low charge using the PCA method.

The results also show that PCA method has obvious advantages in data processing at lower charge. At ultra-low charge about 1.5 pC, the resolution can also achieved 30 fC which indicates the superiority of the cavity probe in the measurement of ultra-low beam charge.

EVALUATED BY DOUBLE-CAVITY MIXING METHOD

Based on the mixing of the cavity with the LO, a method of double-cavity mixing was proposed. Since the amplitude of the cavity TM010 mode is proportional to the beam charge, the IF signal obtained by double-cavity mixing is proportional to the square of the beam charge theoretically. The advantages of the double-cavity mixing method is that it does not need to provide an external LO and the signals are related to the beam. In addition, a square relationship related to the beam charge is introduced, it can improve the resolution of the square root of 2 times theoretically.

The schematic diagram shown in Fig. 9 is to verify the relation between beam charge and the amplitude of double-cavity mixing. The cavity signal mix with the LO as the real beam charge to compare the results of double-cavity mixing.

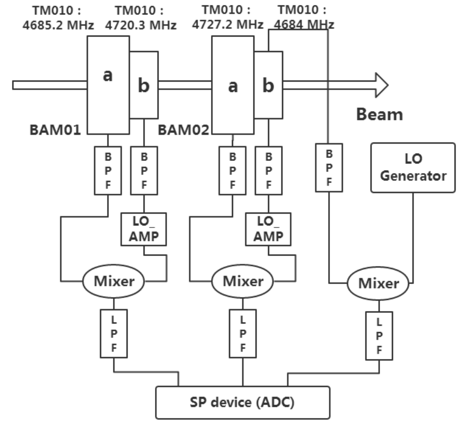

Figure 9: Diagram of the double-cavity mixing.

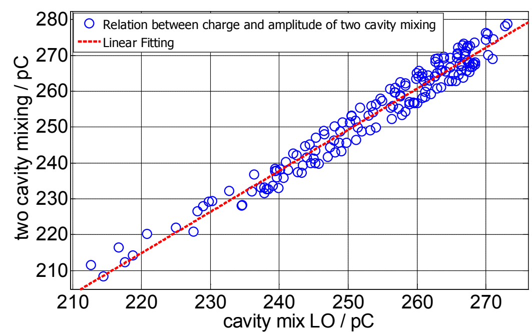

Figure 10: Relation between beam charge and the root of the amplitude of double-cavity mixing.

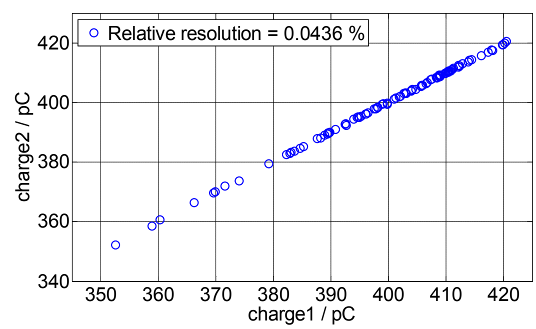

Figure 11: Relative resolution result using the method of double-cavity mixing when the charge is about 400 pC.

The relationship between the beam charge (cavity mixed with LO) and the root of the amplitude of double-cavity mixing was shown in Fig. 10. The results prove that the amplitude of double-cavity mixing is proportional to the square of the beam charge. Using this method we also evaluate the relative resolution of 0.0436% when the charge is about 400 pC (Fig. 11).

CONCLUSION

According to the principle that the signal amplitude of the cavity TM010 mode is proportional to the beam charge, the method mixing with the LO signal was used and get the relative resolution is about 0.08% when the beam charge is about 500 pC. In addition, double-cavity mixing method to evaluate the beam charge was proposed

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and preliminary experiment also has been down which can get the relative resolution of 0.0436% when the charge is about 400 pC. All of which demonstrate the superiority of Cavity BPM in beam charge measurement.

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