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RESEARCH ON THE OPTIMAL AMPLITUDE EXTRACTION ALGORITHM FOR CAVITY BPM*

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Abstract

The wake field of different modes of cavity BPM carries different bunch information, the amplitude and phase of the signals of different modes can be extracted through the signal processing method to obtain the characteristic parameters of the source bunch. In the application of bunch charge and position measurement, the accurate amplitude extraction method for cavity BPM signal is the primary issue to be considered when designing the data acquisition and processing system. In this paper, through theoretical analysis and numerical simulation, it is proved that the optimal algorithm of amplitude extraction for CBPM exists, and the dependence between the data processing window size and the decay time of the cavity BPM under the optimal design is given. In addition, the relationship between the optimized amplitude extraction uncertainty and the noise-to-signal ratio, sampling rate of data acquisition and processing system, and the decay time of the cavity BPM is also proposed, which can also provide clear guidance for the design and optimization of the CBPM system.

INTRODUCTION

Cavity BPM (CBPM) adopting a resonant cavity structure and using the characteristic modes excited by the electron beam to measure the beam parameters, has the advantage of high resolution and is widely used in FEL facilities and Linear Colliders. A typical CBPM system is composed of a cavity pickup, a radio frequency signal conditioning front end, and a data acquisition and processing electronic. The factors that affect system performance mainly include the signal-to-noise ratio (SNR) of the cavity pickup, crosstalk between different modes, beam trajectory with a finite angle, noise figure of RF front-end, performance of Analog to Digital Converter (ADC) and digital signal processing algorithms.

For cavity BPM pickups, it can be divided into low-Q (Quality factor) and high-Q from the Q value of the pickup. In theory, as long as the ADC sampling rate and number of bits are high enough, the multi-point sampling of the signal can always obtain a processing gain greater than 1. Therefore, the best signal acquisition and processing method must be the amplitude and phase extraction after full waveform sampling.

However, in the actual measurement system, due to the limitation of sampling rate and effective number of bits of ADC, when the Q value is exceedingly small, the duration time of signal is short, the data acquisition and processing schemes mostly choose analog IQ demodulation combined with peak sampling of phase locked. However, since this paper discusses general rules, technical limitations of ADC are not specifically considered.

As for the high-Q cavity BPM system, in terms of data acquisition and processing methods, the conventional method is to sample and quantize the full waveform of the IF signal conditioned by the RF front-end. And then the amplitude and phase information were extracted in the digital domain by the algorithm such as digital down-conversion (DDC), time-domain fitting, harmonic analysis, etc. In general, all waveform data are used in digital signal processing, and there is no systematic research on the optimal signal processing method. In addition, for the design and optimization of the system, there is also have no clear guiding formula for the parameters selection among the various components of the CBPM system.

In this paper, based on theoretical analysis and numerical simulation, the optimal algorithm of amplitude extraction for CBPM is discussed, and the guidance formula about the optimized amplitude extraction uncertainty and the parameters of CBPM system is also studied.

THEORETICAL ANALYSIS

The output signal of the cavity BPM can be expressed by the Eq. (1):

$$V_{port}(t) = A \cdot e^{-\frac{t}{\tau}} \cdot \sin(\omega t + \varphi). \quad (1)$$

So, the envelope of the signal can be expressed by:

$$y_{sig} = A \cdot e^{-t/\tau}. \quad (2)$$

Assume the white gaussian noise level of the signal can be expressed by:

$$y_n = A \cdot \sigma. \quad (3)$$

Where σ represents the relative noise-to-signal ratio.

The number of data points of the signal waveform after being quantized by ADC is represented by N, and the sampling rate of ADC is represented by Fs, when taking N points for digital signal processing, the total signal can be written as:

$$y_{signal} = \sum_{n=1}^{N} A \cdot e^{-\frac{n}{F_s \cdot \tau}}. \quad (4)$$

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Since noise is superimposed incoherently, the total noise can be written as:

$$y_{noise} = A \cdot \sigma \cdot \sqrt{N} \quad (5)$$

So, when selecting *N* points of waveform data for digital signal processing, the relative amplitude extraction uncertainty can be expressed as:

$$\frac{y_{noise}}{y_{signal}} = \frac{A \cdot \sigma \cdot \sqrt{N}}{\sum_{n=1}^{N} A \cdot e^{-\frac{n}{F_s \cdot \tau}}} \approx \frac{\sigma \cdot \sqrt{N}}{\tau \cdot F_s \cdot (1 - e^{-\frac{N}{F_s \cdot \tau}})} \quad (6)$$

Denote *N* by *T* and *Fs*, the Eq. (6) can be simplified to:

$$\frac{y_{noise}}{y_{signal}} = \frac{\sigma \cdot \sqrt{T}}{\tau \cdot \sqrt{F_s} \cdot (1 - e^{-\frac{T}{\tau}})} \quad (7)$$

Therefore, take the derivative of Eq. (7), the relationship between the *T* and each parameter under the minimized amplitude extraction uncertainty can be found, the result is reduced as:

$$(\frac{2T}{\tau} + 1) \cdot e^{-\frac{T}{\tau}} = 1 \quad (8)$$

After solving, we get that the relationship between the optimal data processing window size (*T*) and the signal decay time (τ) under the minimized amplitude extraction uncertainty is:

$$T = 1.257 \cdot \tau \quad (9)$$

The theoretical analysis results show that the optimal data processing window size of the cavity BPM signal exists, and irrelevant to the sampling rate, effective bits of the ADC and the noise-to-signal ratio of the signal, but only with the decay time (loaded Q value) of the cavity BPM. This is the balance between the noise-to-signal and the signal processing gain, which minimizes the amplitude extraction uncertainty.

Substituting Eq. (9) into Eq. (7), so that the relationship between the amplitude extraction uncertainty and the relative noise-to-signal ratio (σ), sampling rate of data acquisition and processing system (*Fs*), and the decay time of the cavity pickup (τ) under the optimization algorithm can be obtained, expressed by Eq. (10), which also has an important guiding sense for the design and optimization of the Cavity BPM system.

$$R = 1.567 \cdot \frac{\sigma}{\sqrt{\tau \cdot F_s}} \quad (10)$$

BEAM EXPERIMENT

Shanghai Soft X-ray FEL (SXFEL) is the first coherent X-ray light source in China, and cavity BPMs are installed for measure the beam position precisely. Based on the theoretical analysis mentioned above, in order to verify the relationship between the system parameters and the best window size under beam conditions, some experiments are designed, and cavity BPMs and BAMs with different parameters were selected at the SXFEL. The parameters of cavity pickups are listed in Table 1.

Table 1: Parameters of Cavity Pickups at SXFEL

	CBPM1-X	CBPM1-REF	BAM1	BAM2
Resonant frequency (MHz)	4681.8	4696.0	4720.3	4685.2
Decay time (ns)	320	144	300	298

The signals excited by the X and REF cavities of CBPM1 with different decay time are compared to verify the quantitative relationship between decay tine and the best window size. The power divider is used to divide the IF signal of REF and X and then be quantized by the ADC with resolution of 16 bit and sampling rate of 476 MHz, so as to remove the effect of bunch charge jitter. As shown in Fig. 1, the best window sizes of REF cavity and X cavity with different decay time are 1.27 times and 1.29 times of their respective decay time, it is in good agreement with the theoretical analysis and simulation results, and the corresponding amplitude extraction uncertainty has also been greatly improved. In addition, in order to evaluate the impact of sampling rate and number of bits of ADC on the best window size, the REF cavity of CBPM1 was selected, and using the same evaluation method but different DAQ system for data acquisition, including home-made Digital BPM (DBPM) processor[1] and QT7135, Libera digit-500 and NI's 5772. The parameters of different DAQs and the corresponding normalized best window sizes are listed in Table 2. The beam experiment results show that within the calculation error range, the best window size is irrelevant with the sampling rate and number of bits of ADC.

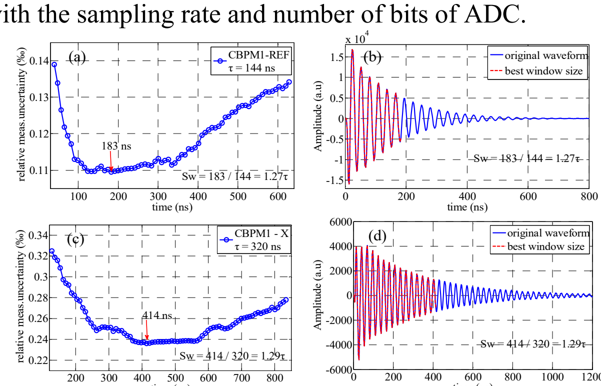

Figure 1: (a) Relationship between data window size and relative measurement uncertainty of REF cavity. (b) waveform of best window size and original data. (c) Relationship between data window size and relative measurement uncertainty of X cavity. (d) waveform of best window size and original data.

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Table 2: Comparison Results of DAQ with Different Parameters (CBPM1 REF τ = 144 ns)

	DBPM	Libera digit 500	NI-5772	QT 7135	
Sampling rate (MHz)	119	476	476	476	952
Resolution (bits)	16	14	12	16	16
Best window size	1.28 τ	1.31 τ	1.30 τ	1.27 τ	1.28 τ

Adjust the parameters of the electron gun, the bunch charge was changed from 15 pC to 180 pC, and the signal coupled by two adjacent BAM pickups with similar decay time but different resonant frequencies [2]. Under different bunch charges, the signal of BAM pickups has different SNR. The local oscillator signal of 4654.2 MHz down-converts the RF signals of BAM1 and BAM2 to IF about 66.1 MHz and 31 MHz, respectively. which can evaluate the effects of different SNR and different signal frequency on the best window size. The results of the beam experiment are shown in Fig. 2. The best window size is about 1.29 times the decay time of the cavity under different bunch charges, which has no obvious dependence on the SNR of the signal and the frequency of the IF signal.

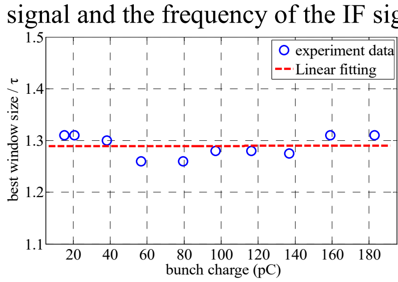

Figure 2: Normalized best window size at different bunch charge.

APPLICATION IN CBPM OF SXFEL

For the SXFEL, in order to provide accurate measurement of the beam orbit and use it for orbit correction to find the ideal orbit of the electron beam, a cavity BPM system consisting of a C-band cavity pickup, a single-stage down-conversion RF front-end and a dedicated digital BPM processor (DBPM) were developed. The system schematic of the cavity BPM system is shown in Fig. 3.

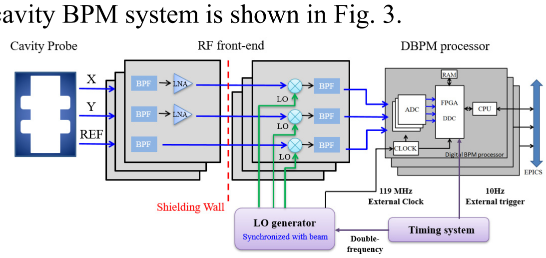

Figure 3: System schematic of the cavity BPM system.

When designing the cavity, to greatly reduce the influence of crosstalk between cavities, the resonant frequency of the position cavities and the reference cavity are designed slightly different [3, 4], and the corresponding loaded Q is also different. The RF front-end with low noise-figure and phase-locked with reference clock to down-converted the RF signal to low IF about 35 MHz and adjust the amplitude to be close to the full scale of the ADC. The data acquisition and signal processing use the home-made DBPM processor, the analog bandwidth is 650 MHz, the resolution is 16 bit, and the maximum sampling rate is 125 MHz.

Three adjacent CBPM pickups were installed at the drift section to evaluate the performance of the system. In the experiment, about 600 sets of data with original data length of 4.2 μs were sampled by the DBPM and processed offline. For the evaluation data we sampled, compare the position resolution results calculated by the typical all waveform data and the method of introducing the best window size into the algorithm. As shown in Fig. 4, the blue lines are the original waveform data of the Y direction of the three CBPMs and the REF channel of CBPM1, and the red lines is the best window size of the corresponding channels at the best resolution obtained. And Fig. 5 show the results of the system position resolution evaluated under the original waveform data and the best window size, respectively.

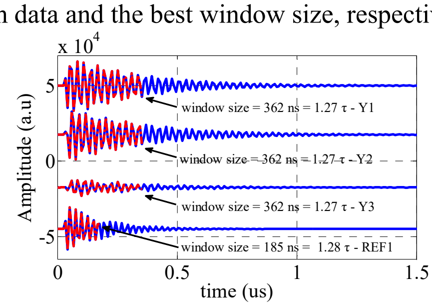

Figure 4: The original waveform and the best window size of the corresponding channels at the best resolution.

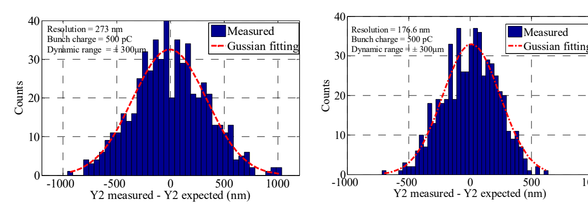

Figure 5: (left) Position resolution of the system at original waveform data. (right) position resolution at best window size.

It can be seen that the best data window sizes are about 1.27 and 1.28 times the decay time of the respective cavities, which is consistent with the theoretical analysis results, and on the other hand, it also verified that the best window size has no dependence on the SNR of source signal or the noise figure of RF front-end. Under the best window size, the calculated beam position resolution of Y direction can reach 177 nm @500 pC·±300 μm. Compared with the 273 nm calculated from the original waveform data, the performance is improved by nearly 30%, so this algorithm can be applied in online CBPM system for further performance optimization.

CONCLUSION

Cavity BPM is widely used in FEL facilities for accurate measurement of beam position. The accurate amplitude ex-

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traction method for cavity BPM signal is particularly important to the performance of the system. This research proposes an optimal amplitude extraction algorithm for the data processing of cavity BPM signal, and the guidance formula about the optimized amplitude extraction uncertainty and the parameters of CBPM system is also studied for the first time. Based on theoretical analysis and numerical simulation methods, the general solution of the best window size was determined to be about 1.26 times the decay time. The beam experiment results on SXFEL also verified the superiority and practicality of this algorithm, and be expected to be applied in SXFEL user facility and the SHINE for further performance optimization.

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