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

- A typical CBPM system: Cavity pickup, RF front-end, DAQ system
- Factors affect system performance: SNR of the cavity pickup, crosstalk between different modes, beam trajectory with a finite angle, NF of the RF front-end, performance of ADC, DSP
- In theory, as long as the ADC sampling rate and EBOB are high enough, the multi-point sampling can always obtain a processing gain > 1.
- Therefore, the best signal acquisition and processing method must be the amplitude and phase extraction after full waveform sampling.
- Due to the limitation of sampling rate and EBOB of ADC, when the Q value is exceedingly small, 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.
- For high-Q CBPM system, for 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 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:

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

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

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

- Assume the white gaussian noise level of the signal can be expressed by: (σ represents the relative noise-to-signal ratio)

$$y_n=A\cdot\sigma$$

- The number of data points 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:

$$y_{signal}=\sum_{n=1}^{N}A\cdot e^{-\frac{n}{F_s\cdot\tau}}$$

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

$$y_{noise}=A\cdot\sigma\cdot\sqrt{N}$$

- The relative amplitude extraction uncertainty can be expressed as:

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

- The relationship between the best window size (*T*) and signal decay time (τ) under the minimized amplitude extraction uncertainty is:

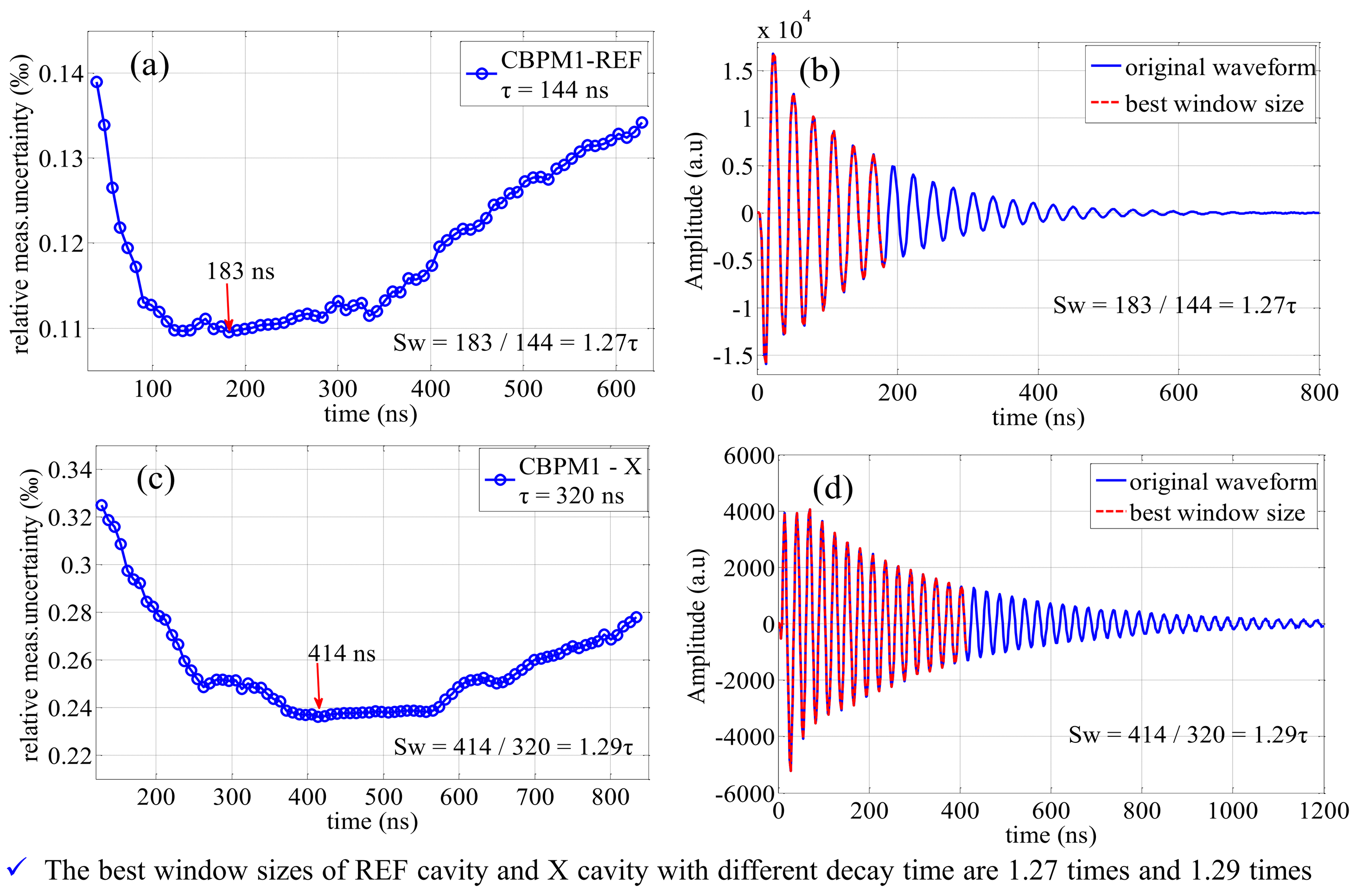
$$T=1.257\cdot\tau.$$

- Substituting the results, the relationship between the amplitude extraction uncertainty and the relative noise-to-signal ratio (*σ*), sampling rate of the processing system (*Fs*), and the decay time (*τ*) under the optimization algorithm can be obtained:

$$R=1.567\cdot\frac{\sigma}{\sqrt{\tau\cdot F_s}}=1.567\cdot\frac{\sqrt{(G_{RFFE}\cdot NF\cdot N_{RF})^2+(N_{adc})^2}}{G_{RFFE}\cdot A_{RF}}\cdot\sqrt{\frac{1}{\tau\cdot F_s}}$$

Beam experiment

- 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 the Table1 .



✓ 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 the corresponding amplitude extraction uncertainty has also been greatly improved

Table 1: Parameters of Cavity Pickups at SXFEL

	CBPM1-X	CBPM1-R	BAM1	BAM2
Frequency (MHz)	4681.8	4696.0	4720.3	4685.2
Decay time	320 ns	144 ns	300 ns	298 ns

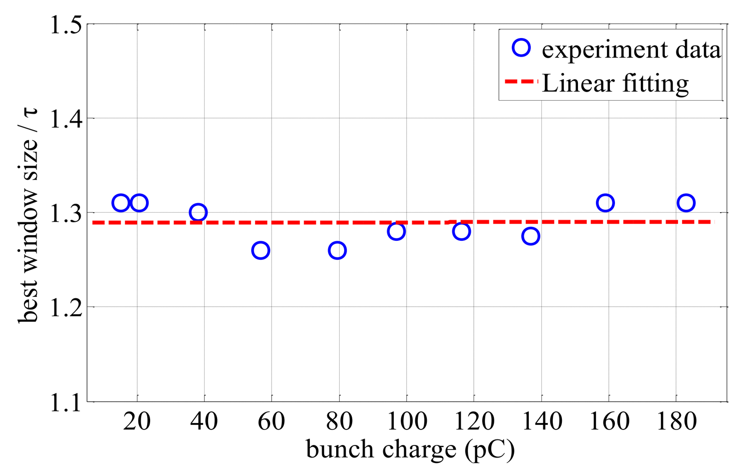
- To evaluate the impact of sampling rate and ENOB of ADC on the best window size, using the same evaluation method but different DAQ system for data acquisition. The parameters of different DAQs and the corresponding normalized best window sizes are listed in Table 2.

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

	DBPM	Libera digit 500	NI-5772	QT7135	
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

✓ Within the calculation error range, the best window size is irrelevant with the sampling rate and number of bits of ADC

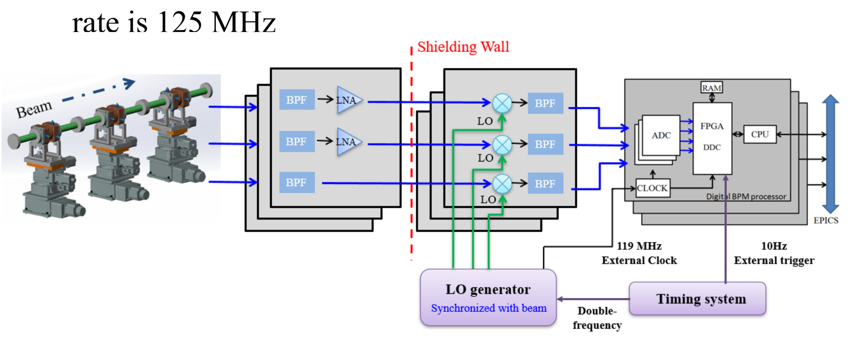
- Adjust the bunch charge from 15 pC to 180 pC, to evaluate effects of different SNR and different signal frequency (IF of BAM1 and BAM2 are 66.1 MHz and 31 MHz, respectively) on the best window size:



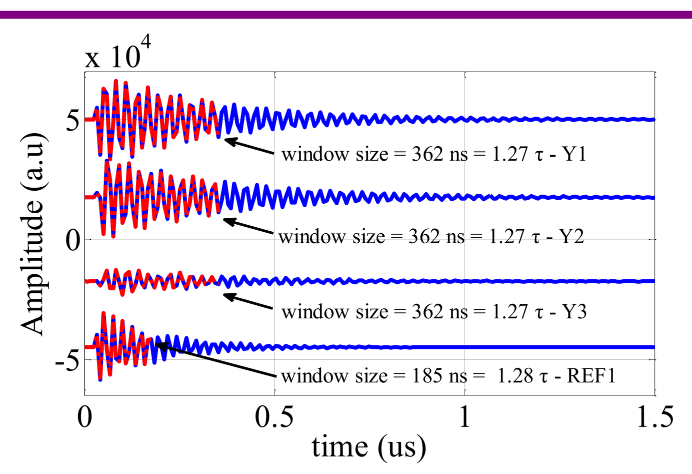
✓ The best window size is about 1.29 times the decay time of the cavity under different bunch charges, which has no obvious dependence on the SNR of the signal and the frequency of the IF signal

Application in CBPM of SXFEL

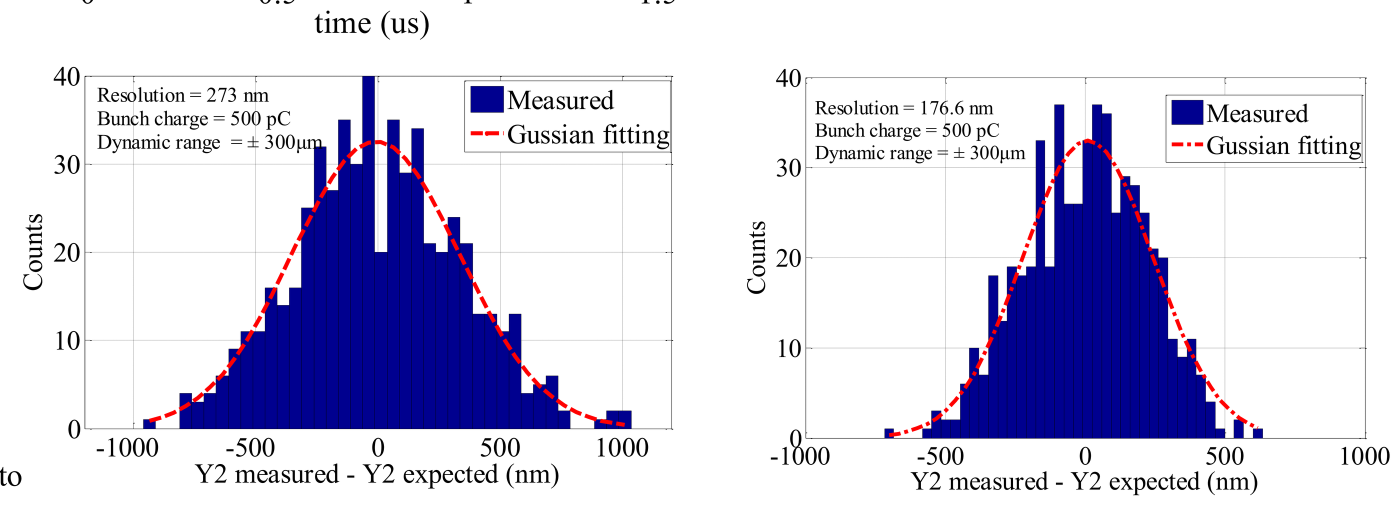
- Cavity BPM system in SXFEL facility:
  - ✓ C-band high-Q cavity pickup, the resonant frequency of the position and the reference cavities are designed slightly different to reduce the influence of crosstalk between cavities
  - ✓ RF front-end with low noise-figure and phase-locked with reference clock to down-converted the RF signal to low IF about 35 MHz
  - ✓ 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. About 600 sets of data with original data length of 4.2 μs were sampled and processed offline



✓ 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.



Resolution was optimized from 273nm to 177 nm under best window size

Conclusion

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