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THE ALGORITHM RESEARCH OF DBPM FOR HEPS

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Abstract

The High Energy Photon Source (HEPS) is a 6-GeV, low-emittance, 1300m scale new generation photon source to be built in China [1]. As a key component, digital beam positon monitor (DBPM) needs to make the beam slow acquisition's resolution up to 0.1um. Because of the high requirements and large expenses, we designed our own DBPM system. In this paper, I will present the algorithm of our BPM. The algorithm is based on Discrete Fourier Transform (DFT) method and tested in BEPCII with using our own designed hardware. The Turn-by-Turn's resolution tested in BEPCII is 0.62um (STD value, 65080 counts, 1.2432MHz), the fast acquisition's resolution is 0.32um (STD value, 65080 counts, 10kHz), the slow acquisition's resolution is 0.18um (STD value, 65080 counts, 10Hz).

INTRODUCTION

Beam orbit stability is one of the most critical performance indicators of modern synchrotron radiation sources. The stability of the beam orbit directly affects the performance of the accelerator and the quality and stability of the light experimental station. Synchrotron radiation sources require a beam orbit variation of less than 5% to 10% of the beam size. For HEPS, the minimum beam diameter of the storage ring is about 3μm, and therefore the resolution of the beam position monitor (BPM) is required to reach 0.1μm. The orbit control accuracy reaches 0.3μm. The circumference of the storage ring for HEPS is approximately 1300 meters, requiring more than 700 BPMs. Due to the large cost of such a number of commercial products purchased, we have developed our own digital BPM system. The signal processing algorithm involved is the key to its realization [1,2].

Because the HEPS test facility (HEPS-TF) is underway, we can only use BEPCII as the experimental platform to build the digital signal processing BPM algorithm based on DFT. So our digital signal processing BPM algorithm based on the DFT method is based on the BEPCII parameters. This article will first briefly introduce the overall hardware structure of the system, after which the algorithm based on the DFT method will be described in detail. Finally, the results of experiments performed on the BEPCII will be given.

HARDWARE STRUCTURE

The digital BPM electronics system for HEPS is based on the MTCA.4 structure and is divided into a front-end analog signal processing board called Rear Transition Module (RTM) and a digital processing signal board called Advanced Mezzanine Card (AMC). The front-end analog signal processing card adjusts the four BPM pick up signal to the ±10 MHz bandwidth signal that is acceptable by the ADC and centered on the RF frequency through multi-step amplification and attenuation. Then sent to the digital signal processing card to preform ADC sampling and processing. The structure of our RTM and AMC card are shown in Fig. 1.

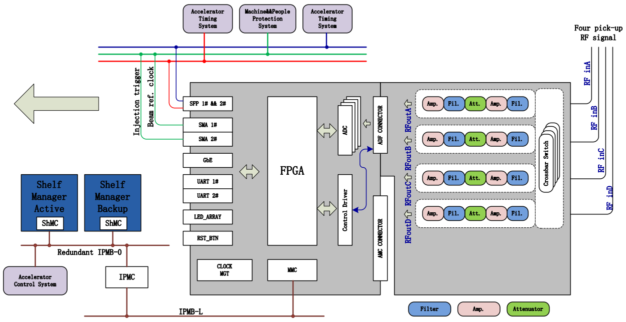

Figure 1: Structure of our RTM and AMC card.

The AMC card uses a 16-bit ADC to sample the signal. It also need to complete the algorithm processing and data transmission function. The ADC sampling clock is synchronized to the input revolution frequency, which is given by the accelerator timing system.

SIGNAL PROCESSING ALGORITHM

The algorithm mainly converts the bandpass sampling signal, in the range of the revolution frequency bandwidth centered on the RF frequency, to the fundamental frequency. And then obtains the position information through decimation and difference/sum method. The light source is currently in the TF stage, so the algorithm has to be designed with the BEPCII's parameter,and then test in BEPCII.

Parameters Selection

The BPM pick up signal is processed by the front-end RF analog circuit to a 10MHz bandwidth signal centered around the RF frequency, which is 499.8MHz. To improve the sampling accuracy, we choose high 16-bit ADC. The resolution frequency of BEPCII is 1.2621MHz in collider mode and 1.2433MHz in synchrotron radiation mode.

For band-pass sampling, the sampling frequency $f_s$must satisfy $f_s = 4f_0/(2n+1)$, and when the bandwidth is $2B \le f_s$, the acquired signal will be able to accurately restore the original signal. Therefore, we can use high-accuracy low-rate ADC to get an accurate measurement results.

To ensure the frequency coherence of the processed signal and restore the signal spectrum. The sampling frequency should meet the following condition:

- The sampling frequency must be an integer multiple of the revolution frequency;

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- RF frequency must fall within the odd Nyquist domain which is periodic in sampling frequency, and it is best to approach the center of the domain.

Because of we use a nearly 200MHz ADC, we located the sampling frequency of collider mode at 116.1152 MHz, which is 92 times the revolution frequency, and located the sampling frequency of synchrotron radiation mode at 118.1119 MHz, which is 95 times the revolution frequency, and making the RF frequency fall in the 9th Nyquist domain which is periodic in sampling frequency, i.e., $f_s = 4f_0/(2n+1)$, where n is 4.

Fast feedback position requires a bandwidth of 10 kHz and the output data rate is same, which is approximately 1/126 times the revolution frequency for the collider mode, and approximately 1/124 times the revolution frequency for synchrotron radiation mode, making bandwidth and output data rate of fast acquisition (FA) approximately equal to 10.0169kHz in collider mode and 10.0265KHz in synchrotron radiation mode.

The rate of slow acquisition (SA) positon requires 10 Hz, which is about 1024 times lower than the FA rate. The SA rate of collider mode is 9.7821Hz. In synchrotron radiation mode is 9.7915Hz.

The summary of BPM parameter selection based on BEPCII is shown in Table 1.

Table 1: Summary of BPM Parameters

Parameter	**Collider mode**	**Synchrotron radiation mode**
RF frequency [MHz]	499.8	499.8
Harmonic number	396	402
Revolution frequency [MHz]	1.2621	1.2433
Sampling frequency [MHz]	116.1151	118.1119
TBT Decimation	92	95
FA decimation	124	126
FA date rate [Samples/s]	10016.9	10026.5
SA decimation	1024	1024
SA date rate [Samples/s]	9.7821	9.7915

DFT-based Algorithm

After the band-pass sampling, the spectrum will be periodic recurrence at the sampling frequency. The input 20MHz bandwidth signal centered on the high frequency is also reproduced in periodic. After band-pass sampling, the high frequency will fall in the first Nyquist domian at 35.3394 MHz in collider mode, 27.3522 MHz in synchrotron radiation mode. In order to get the position information, the spectrum needs to be moved to the fundamental, that is, the digital down conversion process. We will use DFT method to achieve the shift of spectrum. The structure of the DFT algorithm is shown in Fig. 2.

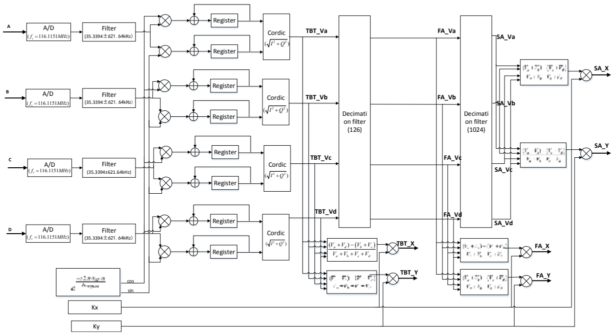

Figure 2: Structure of DFT algorithm.

- Pre-filter

  In order to prevent aliasing and improve the measurement accuracy, we added a filter before implementing the DFT algorithm. So that make the input signal bandwidth is the revolution frequency, centered on RF frequency, in the first Nyquist region after band-pass sampling. That is, in collider mode it centered around 35.3394 MHz, in synchrotron radiation mode it centered on 27.3522 MHz, and each having a left and right revolution frequency bandwidth signals.
- DFT down conversion

  The DFT-based down-conversion is mainly achieved by calculating the N-point DFT at the high frequency after bandpass sampling. The DFT down conversion use the following formula:

$$X[h_{IF}] = \sum_{n=0}^{h_{samples}} x[n].e^{\frac{-i\cdot 2\pi\cdot h_{IF}\cdot n}{h_{samples}}}$$

$$n = 0,1\cdots, samples - 1$$

For collision mode, the input signal rate is 92 times the revolution frequency. In order to obtain TBT data, 92 DFT calculations are required. Because of the collision mode, the RF frequency rate after bandpass sampling moves to 35.3394 MHz, which is 28 times the revolution frequency. Therefore, we need to calculate the amplitude of its 28th spectrum. Then finish the down conversion process. In the synchronous mode, since the bandpass sampled RF spectrum was shifted to 27.3252 MHz, which was 22 times the revolution frequency, and the sampling frequency was 95 times the revolution frequency, it was just necessary to calculate the amplitude at the 22nd peak of the 95-dot DFT. The calculation parameters are shown in Table 2 [3,4].

Table 2: DFT Parameters

Parameter	**Collider mode**	**Synchrotron radiation mode**
f_{RF}	499.801MHz	499.801MHz
h	396	402
$h_{samples}$	92	95
h_{IF}	28	22

- Amplitude and position calculation

  After DFT down-conversion, due to the twiddle factor, the DFT signal is composed of two orthogonal IQ signals. Therefore, the two signals need to be squared by CORDIC, and then use square root algorithm to obtain the amplitude information. After that, the difference/sum method is used to calculate the position information. The formula for calculating the normalized electrode signal, using difference/sum method, is shown as follows:

$$\begin{cases} \mathrm{U} = \dfrac{(V_a + V_d) - (V_b + V_c)}{V_a + V_\mathrm{b} + V_c + V_d} \\ V = \dfrac{(V_a + V_b) - (V_c + V_d)}{V_a + V_\mathrm{b} + V_c + V_d} \end{cases}$$

Then multiply the calibration coefficient $\mathrm{k_x}$ and $\mathrm{k_y}$ to get the actual beam position. At this point, this position is turn-by-turn (TBT) positon.

- Calculation of FA and SA position
  From the above, we have obtained TBT position and four amplitude of Va, Vb, Vc,Vd. Then we need to use a decimation filter to complete the filtering and decimation to obtain FA and SA data. Then use the difference/sum method same as TBT to obtain the position information. Now the filters we used are just CIC filter.

TEST IN BEPCII

For this algorithm, we have already completed the FPGA implementation and tested in BEPCII. The following results are the actual beam results on November 22, 2017. At this time, BEPCII works in the synchrotron radiation mode, and the beam current is 250mA.

- TBT data at injection

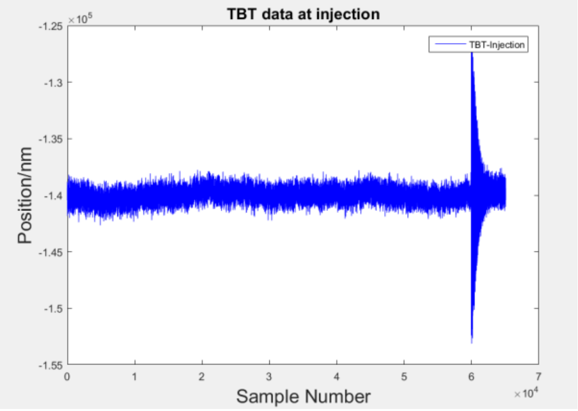

Figure 3: TBT data at injection.

Figure 3 shows the state of injection. The vertical axis represents the TBT y position, and its unit is nanometer. The horizontal axis represents tbt sampling points. The spectrum of these data is shown as follows:

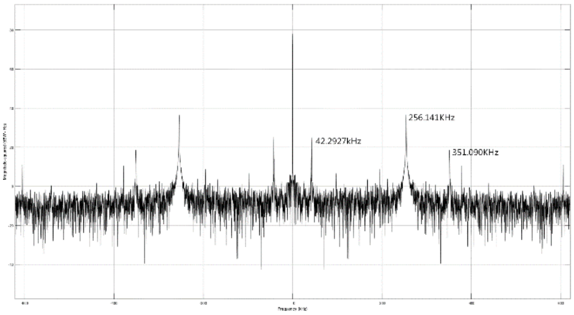

Figure 4: Spectrum of TBT injection data.

From Fig. 4 we can clearly see the frequency of transverse betatron oscillation and longitudinal synchrotron oscillation. The horizontal oscillation frequency is 256.141kHz and the corresponding tune is 0.206. The vertical oscillation frequency is 351.090kHz and the corresponding tune is 0.282. The longitudinal synchrotron oscillation frequency is 42.2927kHz and the corresponding tune is 0.034.

- TBT data

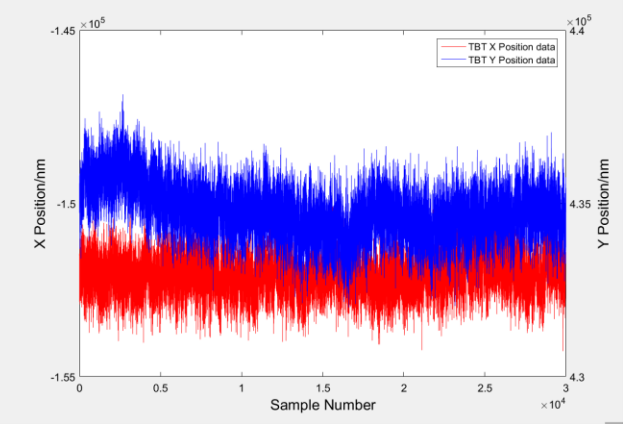

Figure 5: TBT data.

Figure 5 is the original data of TBT from FPGA. The resolution of TBT is shown in Table 3. It shows three sets of TBT data results. It is the STD value. The data counts is 65080.

Table 3: TBT Resolution

TBT_X STD [nm]	**TBT_Y STD [nm]**
773.167569	617.296091
707.543018	607.241255
859.396005	629.550139

- FA data

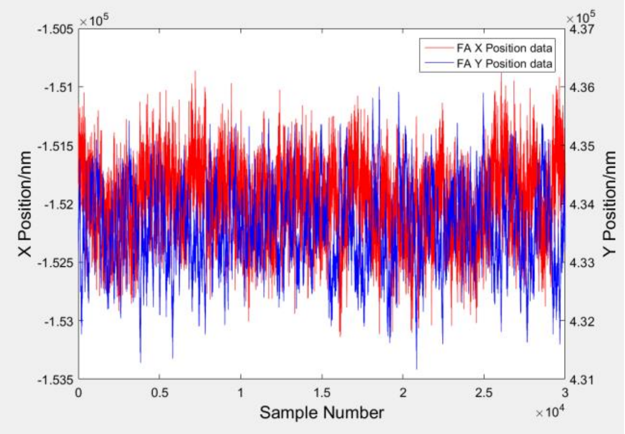

Figure 6: FA data.

The FA data from FPGA is shown in Fig. 6. The resolution of FA is shown in Table 4. It is the 64808 counts STD value. We also give three sets of value.

Table 4: FA Resolution

FA_X STD [nm]	FA_Y STD [nm]
692.298061	312.850909
675.888470	324.749247
638.885257	344.017834

- SA data

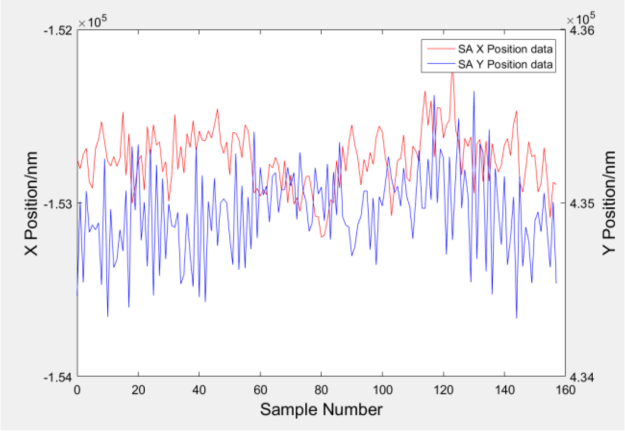

Figure 7: SA data.

The SA data from FPGA is shown in Fig. 7. The resolution of SA is shown in Table 5. It is the 158 counts STD value.

Table 5: SA Resolution

SA_X STD [nm]	SA_Y STD [nm]
295.191632	196.948784
262.266344	169.603390
262.644187	181.012390

CONCLUSION

This paper described the progress and principle of the BPM algorithm based on DFT method. Although it has been verified and measured in BEPCII and takes good results, it still has a long way to go to use it in HEPS. And we will do more research on the all BPM system in the future.

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