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FPGA-BASED DIGITAL IQ DEMODULATOR USED IN THE BEAM POSITION MONITOR FOR HIAF Bring

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Abstract

A digital beam position monitor processor has been developed for the High Intensity heavy ion Accelerator Facility (HIAF). The digital IQ demodulator is used in the Beam Position Monitor (BPM) signal processing. All data acquisition and digital signal processing algorithm routines are performed within the FPGA. In the BPM electronics system, a 250 MHz sample rates ADC was used to digitize the pick-up signal. In the FPGA, the digital signal is filtered by ultra-narrow bandpass filters, then the digital IQ demodulator is used to calculate the beam position with a difference-over-sum algorithm. The heavy ion synchrotron CSRm revolution frequency changes from 0.2 MHz to 1.78 MHz when charged particles. In this design, a Direct Digital Synthesizer (DDS) whose output frequency changes over time is applied to generate the in-phase and quadrature components in the digital IQ demodulator. The performance of this designed BPM processor was evaluated with the online HIRFL-CSRm.

INTRODUCTION

Beam Position Monitor (BPM) is a common non-intercepted beam measurement device used to measure the lateral position of beams in vacuum tubes and is widely used in cyclotrons, linear accelerators, and synchrotrons[1–3], especially in the synchrotrons these monitors are distributed around the ring and used to calculate the closed orbit. HIAF is a high-intensity heavy ion accelerator complex designed by the Institute of Modern Physics, CAS, China. It can provide intense primary and radioactive ion beams for studies in nuclear physics, atomic physics, and related research fields[4]. As shown in Figure 1 it mainly consists of a superconducting electron cyclotron resonance ion source (SECR), a superconducting ion Linac accelerator (iLinac), a booster ring (BRing), high-energy fragment separator (HFRS), and a storage ring spectrometer (SRing). BRing is the main part of HIAF, it could accelerate the proton beam from 48 MeV to 9.3 GeV with an intensity of up to 6.0e12 ppp (particles per pulse)[5]. The ramping rate of BRing dipole magnet is up to 12 T/s and the beam particles are accelerated to the top level energy of less than 300 ms, which means that the revolution frequency of BRing would be changed from 0.2 MHz to 1.78 MHz within this short period[5]. In HIAF, about 40 BPM pich-ups would be distributed around the BRing and the resolution of the BPM should be better than 0.1 mm. An independent research and development full digital prototype of the BRing beam position calculation system was designed. Because the HIAF is under construction, the prototype of the BPM algorithm would first tested and estimated on the HIRFL-CSRm (the main cooling storage ring in the Heavy Ion Research Facility in Lanzhou) which has a similar range of revoluation frequency.

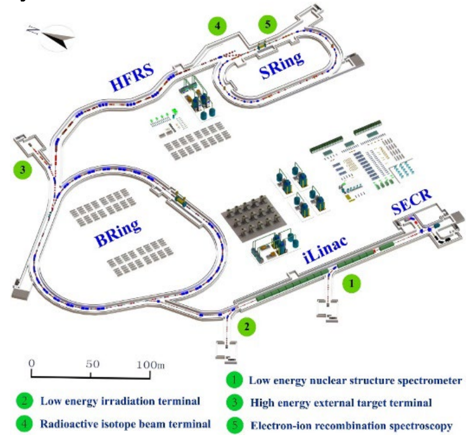

Figure 1: The layout of HIAF.

SYSTEM ARCHITECTURE

The block diagram of the BPM data acquisition is shown in Figure 2. The signal on the pick-up first passes through the front-end amplifier with a gain of about 40 dBm and then travels over a long coaxial cable to the BPM data processing electronics and data acquisition system. In the BPM electronics, high-speed ADCs (analog to digital converter) are employed, and the sample rate is 250 Msps. The main digital signal processing is implemented by a System-on-Chip (SoC) device ZYNQ UltraScale+(ZU15) series. By using the SoC, the data from FPGA to ARM could be easily acquired. Figure 2 is the digital platform of the BPM system architecture.

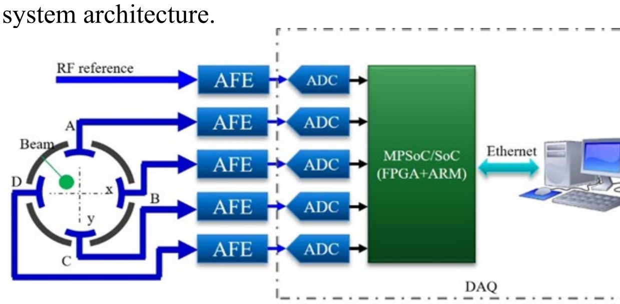

Figure 2: System architecture.

DIGITAL SIGNAL PROCESSING

The sampling frequency of 250 MHz is the main clock frequency in the FPGA. After the ADC sampling the amplified signal from pick-ups, the acquired signal is first passed through a narrow band-pass filter that cuts off high-

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and low-frequency components to ensure that the position calculation process is as unaffected as possible. Since the charged particles in the synchrotron pass through the Radio Frequency (RF) cavity to obtain energy and are accelerated, the RF signal is synchronized with the charged particles. The RF signal is also been acquired. In this design, the RF signal is used to obtain the cyclotron frequency in real time to generate the quadrature components of the digital demodulator. Figure 3 is the digital signal processing of BPM.

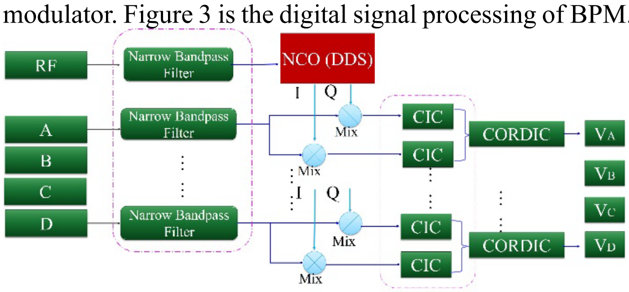

Figure 3: Digital signal processing.

Ultra-narrow Bandpass Filter Implemented in FPGA

The sampling rate is 250 Msps in this design. The revolution frequency of HIAF-BRing is from 0.2 to 1.78 MHz. An ultra-narrow band-pass filter with a frequency in the range of 0.17 ~ 2.5 MHz is necessary. Compared to the ADC sample frequency, the revolution frequency of the synchrotron is located in the low-frequency sideband. In this design, a band-pass filter is designed by combining an FIR low-pass filter and an IIR high-pass filter. The FIR low-pass filter has a pass frequency of 2.5 MHz and a stop frequency of 5 MHz. The coefficients are symmetrical and generated by MATLAB.

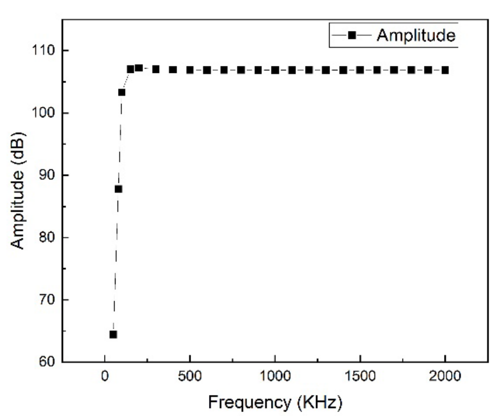

Figure 4: High-pass IIR filter amplitude-frequency response implemented by FPGA.

The high-pass filter is designed by using the IIR (Infinite Impulse Response) filter. Compared to the FIR high-pass filter, the IIR filter is designed in MATLAB and the coefficient matrix is shown in Figure 4. The coefficients of the high-pass IIR filter are then converted to digital signal processing which was programmed by VHDL. Figure 4 shows the amplitude-frequency response of the IIR filter implemented by FPGA.

Digital IQ Demodulator

The digital IQ demodulator[6] is used to calculate each pick-up relative amplitude signal. An NCO (numerical controlled oscillator) is used to generate the sine and cosine digital wave. The input of the NCO is the RF signal set as the reference which could provide the current frequency of the synchrotron. The sine and cosine waves can also be seen as the in-phase and quadrature (in Figure 3 the I and Q) components. NCO is realized by a direct digital synthesizer (DDS). The input of the DDS is the current frequency, output is the sine and cosine wave in digital. The I and Q components mixed with the filtered channel data, as shown in Figure 3 mix module. Then each mixed data channel keeps its DC components by using the CIC decimating filter. The CIC filter's decimate number is 25000. The output of the CIC filter data rate is decreased down to 10 kHz. To calculate each channel's amplitude, the square root function should be applied. In our design, the CORDIC[7] module is used to calculate the square root function. The beam position calculation uses the well-known different-over-sum routine. *Eq. (1)* and *(2)* are used to calculate the horizon and vertical position:

$$x = x_{offset} + kx_1 \frac{VA-VC}{VA+VC} + kx_2 \left(\frac{VA-VC}{VA+VC}\right)^2 \qquad (1)$$

$$y = y_{offset} + ky_1 \frac{VB-VD}{VB+VD} + ky_2 \left(\frac{VB-VD}{VB+VD}\right)^2 \qquad (2),$$

where *VA*, *VB*, *VC*, and *VD* represent the amplitude of each BPM channel respectively. *Kx* and *Ky* are the position coefficients, and the x_{offset} and y_{offset} are deviation values.

LABORATORY AND BEAM TEST RESULTS

Accuracy at Different Input Frequencies

In the laboratory, the input signal power was set to -25 dBm and the input signal was from 0.2 to 2 Mhz with a step of 0.2 MHz. We measured the standard deviation of the BPM electronics.

From Figure 5 we can see that the standard deviation is below 0.3 µm in each test frequency.

Measurement for the long-term stability of the BPM has been tested in the laboratory. The temperature variation in the testing room is < 5 °C. The input power we kept to -25 dBm. Figure 6 shows the position and SUM values of BPM changing as the temperature changes. The various range of position stability is less than 5 µm.

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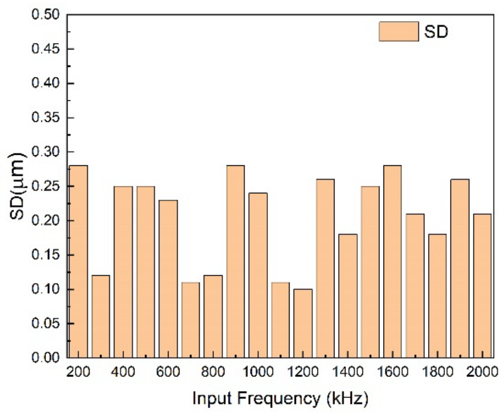

Figure 5: The standard deviation at different input frequencies.

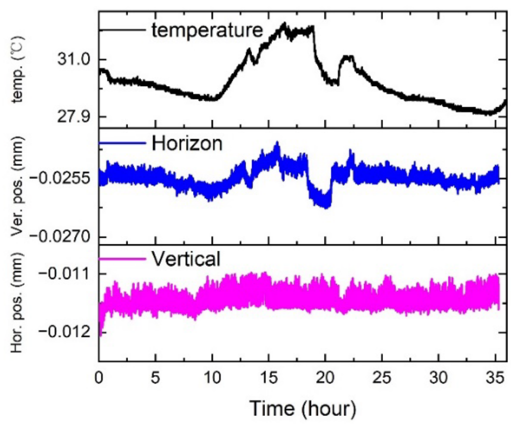

Figure 6: The long-term stability.

Online Beam Test and Comparison

To evaluate the performance of the BPM prototype electronics, its behavior needs to be checked on the real accelerator, the field tests were performed on the HIRFL-CSRm synchrotron. Figure 7 is the beam position measured in horizon and vertical in CSRm. Since CSRm operates in the mode of the second harmonic acceleration, it can be seen that after the completion of the first acceleration, the charged particles in the storage ring changed harmonic from secondary to primary. Because the front-end electronics of the BPM detector work in AC-coupled mode and the beam in vacuum does not have the bunch structure, the BPM system can not detect the beam signal during the harmonic changing period.

The position resolution of the system was estimated by gathering at a quiet spot at about 500 points at 6 seconds in the acceleration cycle. The Root Mean Square of the horizontal and vertical is below 0.03 mm.

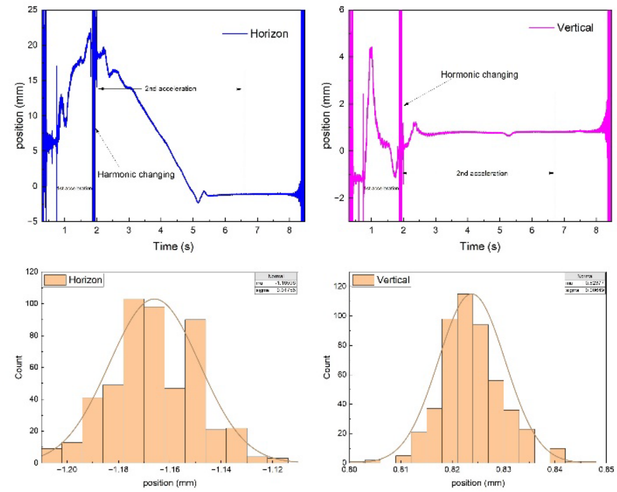

Figure 7: The beam position measured at CSRm and the root mean square. The left is the horizon position and the right is vertical.

We chose the BPM pick-up site which is near the noninvasive Ionization Profile Monitor (IPM)[8] and compared the results between them. Figure 8 (A) is the IPM-detected profile distribution horizon position of the beam. Figure 8 (B) is the beam position detected by BPM and retrieved from the profile distribution of IPM. We could see that the position from BPM could match with IPM.

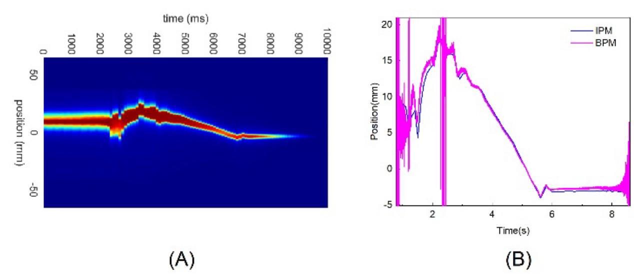

Figure 8: Compare with IPM in horizon position. (A) is the profile distribution horizon position of the beam, (B) is the beam position retrieved from IPM, and the BPM is detected.

CONCLUSION

The newly developed BPM prototype has been tested in the laboratory and with the beam as well. By employing the digital IQ demodulator, the amplitude of each pick-up relative amplitude is retrieved. The RF signal is essential for the NCO to generate the I and Q components in digital real-time. An ultra-narrow bandpass filter which combines an IIR high pass filter and an FIR low pass filter is designed. The laboratory test results show that the resolution of 0.3 µm when the input signal power is -25 dBm and the long-term stability is below 5 µm when the temperature changes. The online beam test comparison shows that the BPM-calculated beam position could match the IPM-detected beam profile results. The resolution of the tested BPM at the field is better than 30 µm which meets the requirements.

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