Application of Real-time Digitization Technique in Beam Measurement for Accelerators

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Abstract: Beam measurement is very important for accelerators. With the development of analog-to-digital conversion techniques, digital beam measurement becomes a research hot spot. IQ (In-phase & Quadrature-phase) analysis based method is an important beam measurement approach, the principle of which is presented and discussed in this paper. The State Key Laboratory of Particle Detection and Electronics in University of Science and Technology of China has devoted efforts to the research of digital beam measurement based on high-speed high-resolution analog-to-digital conversion, and a series of beam measurement instruments were designed for China Spallation Neutron Source (CSNS), Shanghai Synchrotron Radiation Facility (SSRF), and Accelerator Driven Sub-critical system (ADS).

Key words: digital beam measurement; beam phase and position; high-speed analog-to-digital conversion; digital signal processing

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1. Introduction

Accelerators are widely applied in scientific research and many other domains. In China, great efforts are devoted to accelerator-based facilities, such as China Spallation Neutron Source (CSNS), Accelerator Driven Sub-critical system (ADS), Beijing Electron Positron Collider (BEPC), Shanghai Synchrotron Radiation Facility (SSRF), National Synchrotron Radiation Laboratory (NSRL) and Heavy Ion Research Facility in Lanzhou (HIRFL).

High quality beam measurement is very important for accelerators, and thus is a worldwide research hotspot [1-19]. A series of beam measurement techniques were developed for different types of accelerators; however, with higher requirement of beam measurement and development of electronics, more advanced measurement techniques need to be researched for more precise diagnostic of beam parameters.

Traditional beam measurement techniques are based on analog signal manipulation, for example, in Advanced Light Source in USA, Pohang Light Source (PLS) in South Korea, and BEPCII etc. [1-6]. With the development of high-speed high-resolution Analog-to-Digital (A/D) conversion and digital signal processing, digital beam measurement becomes possible. Compared with the analog method, higher precision and flexibility can be achieved. Researchers in many institutes focus on the research in this domain, such as in Low Energy Demonstrator Accelerator (LEDA) [7, 9], Spallation Neutron Source (SNS) in USA [10], Gesellschaft für Schwerionenforschung (GSI) in Germany [11], Institute of High Energy (IHEP), CAS, NRSL [14, 15], SSRF [12, 13, 17]. There are also companies specializing in beam measurement instrument design. For instance, the Libera Electron and Single Pass H series [18, 19] from Instrumentation Technologies (IT) Company in Slovenia are widely employed in accelerators.

As one of the beam measurement research groups, the State Key Laboratory of Nuclear Detection and Electronics also made efforts in this domain, and focused on applying real-time digitization in beam phase (energy)
and position measurement.

This paper is organized as follows. Modern beam phase and position measurement methods based on IQ (In-phase and Quadrature-phase) analysis are discussed, and then three beam measurement systems designed in our research are presented, including the system structure, kernel techniques and performance.

2. Principle of beam phase and position measurement method based on IQ analysis

Beam measurement methods based on IQ analysis are widely used in accelerators [2-7], [9-13], [17-19]. The basic idea is to obtain the I and Q values of the beam Radio Frequency (RF) signals, and then use them for beam measurement.

![Fig. 1 Principle of the beam measurement based on IQ analysis method.](image)

As shown in Fig. 1, by filtering the beam RF signal, a sinusoid signal can be obtained, which corresponds to the component of a certain order of harmonic in the RF signal; then if we can obtain the I and Q values, the phase information of the beam can calculated as:

$$\theta = \arctan \left( \frac{I}{Q} \right)$$  \hspace{1cm} (1)

Meanwhile, the signal amplitude can also be calculated as:

$$Amplitude = \sqrt{I^2 + Q^2}$$  \hspace{1cm} (2)

Special pickups will be used for beam position measurement. For example, in the Storage Ring in SSRF, Beam Position Monitor (BPM) pickups are employed. As shown in Fig. 2, when the beam passes through the cross section of the BPM, four signals are generated through A, B, C, and D. By calculating the amplitudes of these four signals as in (2), beam position can be finally obtained according to the $\Delta/\Sigma$ algorithm, as in

$$x = K_x \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D}$$  \hspace{1cm} (3)

$$y = K_y \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D}$$  \hspace{1cm} (4)

where $V_A$, $V_B$, $V_C$, and $V_D$ refer to the amplitudes of four signals; $K_X$ and $K_Y$ are the effective length factors in X and Y directions.

![Fig. 2 Basic structure of BPM.](image)

The kernel task in IQ analysis is to obtain the I and Q value, the approach for which can be categorized into two main techniques – IQ demodulation and IQ sampling. In both ways, the beam RF signals first pass through Band Pass Filters (BPFs) to extract the fundamental or higher order harmonic, and are then processed by different methods.

![Fig. 3 Block diagram of the IQ demodulation method.](image)

![Fig. 4 Block diagram of the IQ sampling method.](image)

Shown in Fig. 3 are the block diagram of the IQ demodulation method. A sinusoid signal is generated after BPFs and amplifiers, and then split into two paths, which are mixed with two orthogonal Local Oscillator (LO)
signals. The outputs of the mixers can be expressed as 

\[ Y_{R} = \text{Signal}_{in} \times L_{O} \times A \sin(2\pi f_{in}t + \phi) \sin(2\pi f_{LO}t) \]

\[ = \frac{1}{2} A \left[ \cos(2\pi (f_{in} - f_{LO}) t + \phi) - \cos(2\pi (f_{in} + f_{LO}) t + \phi) \right] \]  \hspace{1cm} (5) \]

\[ Y_{L} = \text{Signal}_{in} \times L_{O} = A \cos(2\pi f_{in}t + \phi) \cos(2\pi f_{LO}t) \]

\[ = \frac{1}{2} A \left[ \sin(2\pi (f_{in} - f_{LO}) t + \phi) - \sin(2\pi (f_{in} + f_{LO}) t + \phi) \right] \]  \hspace{1cm} (5)

which indicates that the outputs contain the difference and sum frequency components of the input RF signal frequency \((f_{in})\) and the LO frequency \((f_{LO})\). Passing through Low Pass Filters (LPFs), the two outputs are converted to

\[ O_{R} = \frac{1}{2} A \cos(2\pi (f_{in} - f_{LO}) t + \phi) \longrightarrow \frac{1}{2} A \cos(\phi) \]  \hspace{1cm} (6),

\[ O_{L} = \frac{1}{2} A \sin(2\pi (f_{in} - f_{LO}) t + \phi) \longrightarrow \frac{1}{2} A \sin(\phi) \]

which indicates that the phase \((\phi)\) and amplitude \((A)\) information of the original RF signal are contained in the two outputs \(O_{R}\) and \(O_{L}\). When \(f_{LO}\) is set to be equal to \(f_{IN}\), only DC components remains, which corresponds to the I and Q values. Traditional methods to implement this technique are based on complete analog signal manipulation; nowadays, part of or even complete signal processing can be performed in digital signal processing domain.

As for the other way, IQ sampling, as shown in Fig.4, the sinusoid signal is first down converted to an IF signal. Since down conversion actually consists of the mixer and LPF as in (5) and (6), the IF signal also contains the phase and amplitude information of the original RF signal. Then this IF signal is digitized with a sampling frequency of just four times of the IF signal frequency, so there exist exactly four samples in each period of the digitized IF signal, which are I, Q, -I, and -Q values. With this method, the I and Q values are obtained through sampling, thus the analog circuits complexity is reduced.

We implemented digital beam measurement based on basic idea of the IQ analysis method and designed three beam measurement systems, which will be presented in the following sections.

3. Fully Digital Beam Position Measurement System in SSRF

SSRF is one of the third-generation light sources in the world. In its Storage Ring, up to 720 electron bunches circulate with a duty ratio of 500:220 and a Turn-By-Turn (TBT) frequency of \(f_{mc}=693.964\) kHz. Signals from the BPM pickups are high frequency pulses with a repetition frequency of 499.654 MHz \((f_{mc}\times 720)\). The waveform of single pulse and the frequency spectrum of the pulse sequence are shown in Fig. 5 [13] and Fig. 6, respectively.
The structure of the kernel digital signal processing algorithm is shown in Fig. 9. The digital IF signal is mixed with the two orthogonal outputs from a Numerically Controlled Oscillator (NCO) to obtain the I and Q values, which are then processed by LPF (consisting of CIC filter and FIR filter) to enhance the Signal-to-Noise Ratio (SNR) of the signal while decreasing the data rate from 117.2799 MHz to the TBT rate (693.964 kHz). Through the CORDIC logic, the amplitudes can be calculated with the I and Q values, and then beam position can be finally obtained based on the $\Delta/\Sigma$ algorithm.

A series of tests were conducted to evaluate the system performance both in the laboratory and with the beam in SSRF. Shown in Fig. 10 is the beam position measurement resolution test results, which indicate that the TBT position resolution is better than 10 $\mu$m ($K_3=K_4=10$ mm) within the input signal amplitude range from -40 dBm to 10 dBm.

We also conducted tests on the Libera series of digital beam measurement instruments for performance comparison, which are widely applied in accelerators in the world. Fig. 11 and Fig. 12 are the test results of Libera Electron and its new version Brilliance.
Fig. 13 Setup of the commissioning tests in SSRF.

Fig. 14 and Fig. 15 show the histogram of the Y position measurement results and its frequency spectrum, which correspond to a position resolution of 0.67 μm, and the frequency components close to DC concord well with the beam behavior.

![Histogram of the Y position measurement results](image1)

Fig. 14 Histogram of the Y position measurement results.

![Frequency Spectrum of the Y position measurement results](image2)

Fig. 15 Frequency Spectrum of the Y position measurement results.

We also conducted tests during the beam injection process. The results are shown in Fig. 16, in which the fluctuation can be clearly observed, well as expected. Fig. 17 shows the normalized frequency spectrum of the beam position measurement results of our system and the Libera Brilliance instrument, which indicate the noise floor is almost equivalent.

![Waveform of the Y position measurement results during injection](image3)

Fig. 16 Waveform of the Y position measurement results during injection.

![Frequency Spectrum of the Y position measurement results during injection](image4)

Fig. 17 Frequency Spectrum of the Y position measurement results during injection.

We have finished the design and testing of the electronics systems, and three of them are now used in SSRF. Shown in Fig. 18 is the photograph.

![Photograph of the digital beam position measurement system](image5)

Fig. 18 Photograph of the digital beam position measurement system.
4. Digital Beam Phase and Energy Measurement System in the DTL of CSNS

As shown in Fig. 19, CSNS consists of H− ion source, Radio Frequency Quadrupole (RFQ), Drifting Tube Linac (DTL), Rapid Cycling Synchrotron (RCS) and the target. To guarantee the beam quality in DTL, the system we designed import beam RF signals from Fast Current Transformers (FCTs) in the DTL, and then calculate the beam phase and energy for the beam tuning. Based on the time of flight technique [8], the beam energy can be measured with the beam phase difference information between a pair of FCTs with a known distance. Therefore, the kernel task is beam phase measurement.

![Fig. 19 Layout of CSNS.](image)

**Fig. 19 Layout of CSNS.**

The input beam signals are pulses with a repetition frequency of more than 300 MHz, and its leading edge is around 200 ps. These pulses are further modulated by a macro pulse (repetition frequency is 25 Hz, pulse width is from 50 μs to 500 μs), and a second modulation is conducted with a fine macro pulse with a repetition frequency of 1 MHz and duty ratio of 40:60 to 80:20. Therefore, the beam signal exhibits a complex frequency spectrum; to confirm the validity of the signal processing method, simulations were conducted [25].

![Fig. 21 Frequency spectrum of the modulated signal.](image)

**Fig. 21 Frequency spectrum of the modulated signal.**

As shown in Fig. 21, the frequency is quite complex (as marked in blue color in Fig. 21), as expected. Shown in Fig. 22 is the waveform of the IF signal after down conversion, which indicates almost no distortion in the middle part of the macro pulse despite the waveform at the two ends. The above simulation results verified the correctness of the signal processing method.

![Fig. 22 Simulation results of the signal after down conversion.](image)

**Fig. 22 Simulation results of the signal after down conversion.**

Since the IF signal contains exactly four samples in each period after A/D conversion, i.e. I, Q, −I, and −Q. Then we can calculate the beam phase based on DSP algorithms, which are integrated within one single FPGA, as shown in Fig. 23.
Shown in Fig. 24 and Fig. 25 are the beam phase and energy measurement system and the test platform.

Fig. 24 Photograph of the Analog Front End (AFE) and Digital Processing Board (DPB).

Fig. 25 System under test.

Fig. 26 and Fig. 27 are the test results of the waveform of digitized IF signal, which indicate there exist 4 samples in each period, well as expected.

Fig. 26 Waveform of the digitized IF signal.

Fig. 27 Detailed waveform of the digitized IF signal.

Fig. 28 is the phase resolution test result. The phase resolution is better than 0.1° (@ 367 kHz) over a dynamic range from -50 dBm to 7 dBm, well beyond the required ±0.5°.

Fig. 28 Phase resolution test results.

5. Digital Beam Phase and Position Measurement System in the Proton Linac of ADS

Based on the above research, we proposed a new method to simplify the beam measurement electronics, in which the input beam RF signals are directly under sampled. By precisely tuning the sampling frequency using Phase Locked Loop (PLL) chips, orthogonal
streams (i.e. I and Q arrays) can be obtained. The principle of the technique is shown in Fig. 29.

![Fig. 29 Principle of the direct IQ under sampling method.](image)

Since the I and Q arrays are obtained directly through A/D conversion, compared with the above two systems, complexity of both the analog circuits and DSP algorithms are greatly reduced. We applied this new method in the beam measurement of the proton Linac in ADS, and integrated both beam phase and position measurement within one single instrument.

![Fig. 30 Block diagram of the beam phase and position measurement system.](image)

As shown in Fig. 30, the input signals from the four pickups of BPM are first amplified and filtered by the RF circuits and then directly under sampled by high-speed high-resolution ADCs [26]. By tuning the sampling frequency ($f_s$) using cascaded PLLs, a certain relationship between $f_s$ and the RF signal frequency ($f_{RF}$) can be guaranteed, as in

$$f_s = \frac{4f_{RF}}{4M \pm 1}$$

where M is an integer. Through A/D conversion, a digital IF signal with a frequency of $f_s/4$ can be obtained, i.e. there exist four samples ($I$, $Q$, $-I$, $-Q$) within each IF period.

In this system, two schemes are studied; one is based on the signal processing of the fundamental frequency component of 162.5 MHz, i.e. the repetition frequency of the beam signal, and the other is based on 325 MHz, i.e. the second harmonic of the beam signal. The corresponding sampling frequencies for the above two schemes are 50 MHz and 100 MHz, respectively, which result in digital IF signals of 12.5 MHz and 25 MHz, in good concord with (7). Shown in Fig. 31 and Fig. 32 are the electronics modules and the system under test.

![Fig. 31 Photograph of the Analog Front Ends (AFEs) and Digital Processing Board (DPB).](image)

![Fig. 32 System under test.](image)

Shown in Fig. 33 and Fig. 34 are the test results of the beam phase and position resolution. As for these two schemes, a phase resolution better than 0.2° and a position resolution better than 30 μm are both successfully achieved over a dynamic range from -60 dBm to 0 dBm, well beyond the application requirement.
4 Summary

In this paper, we reviewed the basic beam phase and position measurement techniques, discussed the modern digital beam measurement methods based on the IQ analysis. Three beam measurement electronics systems that we designed were also presented, which are applied or planned to be applied in accelerators in China. Based on the above research, we also expect to apply these techniques in beam measurement of future accelerators.

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