Application of real-time digitization techniques in beam measurement for accelerators*

Lei Zhao(赵雷)[1,2] Lin-Song Zhan(占林松)[1,2] Xing-Shun Gao(高兴顺)[1,2]
Shu-Bin Liu(刘树彬)[1,2] Qi An(安琪)[1,2;1)]

[1] State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China
[2] Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Abstract: Beam measurement is very important for accelerators. In this paper, modern digital beam measurement techniques based on IQ (In-phase & Quadrature-phase) analysis are discussed. Based on this method and high-speed high-resolution analog-to-digital conversion, we have completed three beam measurement electronics systems designed for the China Spallation Neutron Source (CSNS), Shanghai Synchrotron Radiation Facility (SSRF), and Accelerator Driven Sub-critical system (ADS). Core techniques of hardware design and real-time system calibration are discussed, and performance test results of these three instruments are also presented.

Keywords: digital beam measurement, beam phase and position, high-speed analog-to-digital conversion, digital signal processing

PACS: 84.30.-r, 07.05.Hd **DOI:** 10.1088/1674-1137/40/4/046102

1 Introduction

Particle accelerators are widely applied in scientific research and many other domains. In China, great efforts are devoted to accelerator-based facilities, such as the 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 have been developed for different types of accelerators; however, with higher requirements for beam measurement and the development of electronics, more advanced measurement techniques need to be researched for more precise diagnostics of beam parameters.

Traditional beam measurement techniques are based on analog signal manipulation, for example, those used in the Advanced Light Source in the USA, Pohang Light Source (PLS) in South Korea, and BEPCII in China [1–6]. With the development of high-speed high-resolution Analog-to-Digital (A/D) conversion and digital signal processing, digital beam measurement has become possible. Compared with the analog method, higher precision and flexibility can be achieved. Researchers in many institutes focus on research in this domain, including the Low Energy Demonstrator Accelerator (LEDA) [7, 9] and Spallation Neutron Source(SNS) in the USA [10], Gesellschaft für Schwerionenforschung (GSI) in Germany [11], and the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, NRSL [14, 15] and SSRF [12, 13, 17] in China. 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) in Slovenia are widely employed in accelerators.

As one of the beam measurement research groups, the State Key Laboratory of Nuclear Detection and Electronics at the University of Science and Technology of China has 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, core techniques and performance.

Received 6 July 2015

* Supported by National Natural Science Foundation of China (11205153, 10875119), Knowledge Innovation Program of the Chinese Academy of Sciences (KJCX2-YW-N27), and the Fundamental Research Funds for the Central Universities (WK2030040029),and the CAS Center for Excellence in Particle Physics (CCEPP).

1) E-mail: anqi@ustc.edu.cn

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.

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 be calculated as:

$$\theta=\arctan\left(\frac{I}{Q}\right). \tag{1}$$

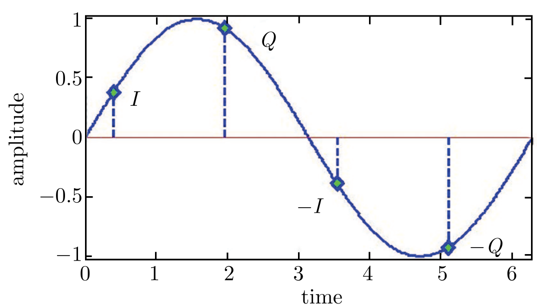

Fig. 1. (color online) Principle of beam measurement based on IQ analysis method.

Meanwhile, the signal amplitude can also be calculated as:

$$\text{Amplitude}=\sqrt{I^2+Q^2}. \tag{2}$$

Special pickups will be used for beam position measurement. For example, in the Storage Ring in the 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 points A, B, C, and D. By calculating the amplitudes of these four signals as in (2), the beam position can be finally obtained according to the Δ/Σ algorithm, as in

$$x=K_x\frac{(V_{\rm A}+V_{\rm D})-(V_{\rm B}+V_{\rm C})}{V_{\rm A}+V_{\rm B}+V_{\rm C}+V_{\rm D}}, \tag{3}$$

$$y=K_y\frac{(V_{\rm A}+V_{\rm B})-(V_{\rm C}+V_{\rm D})}{V_{\rm A}+V_{\rm B}+V_{\rm C}+V_{\rm D}}, \tag{4}$$

where $V_{\rm A}$, $V_{\rm B}$, $V_{\rm C}$, and $V_{\rm D}$ refer to the amplitudes of the four signals, and K_x and K_y are the effective length factors in the x and y directions.

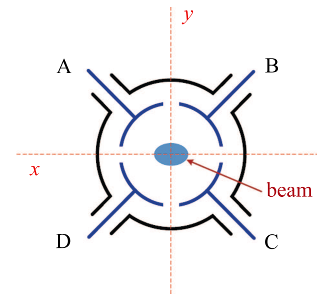

Fig. 2. (color online) Basic structure of a BPM.

The core task in IQ analysis is to obtain the I and Q values, 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.

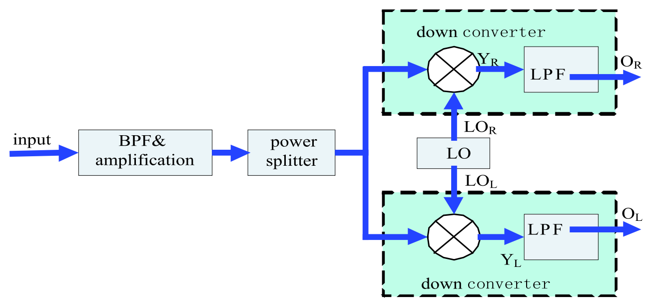

Fig. 3. (color online) Block diagram of the IQ demodulation method.

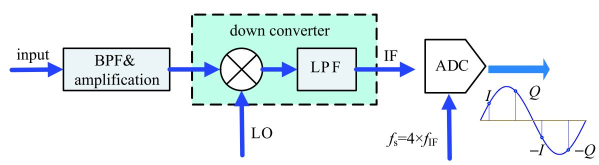

Fig. 4. (color online) Block diagram of the IQ sampling method.

Shown in Fig. 3 is the block diagram of the IQ demodulation method. A sinusoid signal is generated after the 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

$$\begin{aligned} Y_{\rm R}&=\text{Signal}_{\rm IN}\times\text{LO}_{\rm R}=A\sin(2\pi f_{\rm IN}t+\varphi)\cdot\sin(2\pi f_{\rm LO}t)\\ &=\frac{1}{2}A\{\cos[2\pi(f_{\rm IN}-f_{\rm LO})t_{\rm s}+\varphi]\\ &\quad-\cos[2\pi(f_{\rm IN}+f_{\rm LO})t_{\rm s}+\varphi]\} \qquad (5)\\ Y_{\rm L}&=\text{Signal}_{\rm IN}\times\text{LO}_{\rm L}=A\sin(2\pi f_{\rm IN}t+\varphi)\cdot\cos(2\pi f_{\rm LO}t)\\ &=\frac{1}{2}A\{\sin[2\pi(f_{\rm IN}-f_{\rm LO})t_{\rm s}+\varphi]\\ &\quad-\sin[2\pi(f_{\rm IN}+f_{\rm LO})t_{\rm s}+\varphi]\}. \end{aligned}$$

Equation (5) indicates that the outputs contain the difference and sum frequency components of the input

RF signal frequency ($f_{\rm IN}$) and the LO frequency ($f_{\rm LO}$). Passing through Low Pass Filters (LPFs), the two outputs are converted to

$$O_{\rm R}=\frac{1}{2}A\cos\left[2\pi(f_{\rm IN}-f_{\rm LO})t_{\rm s}+\phi\right]\xrightarrow{f_{\rm IN}=f_{\rm LO}}\frac{1}{2}A\cos(\varphi),$$
$$O_{\rm L}=\frac{1}{2}A\sin\left[2\pi(f_{\rm IN}-f_{\rm LO})t_{\rm s}+\phi\right]\xrightarrow{f_{\rm IN}=f_{\rm LO}}\frac{1}{2}A\sin(\varphi), \tag{6}$$

which indicates that the phase (φ) and amplitude (A) information of the original RF signal are contained in the two outputs $Q_{\rm R}$ and $Q_{\rm L}$. When $f_{\rm LO}$ is set to be equal to $f_{\rm IN}$, only DC components remain, which correspond 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 the 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 a mixer and LPF as in Eqs. (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 the IF signal frequency, so there exist exactly four samples in each period of the digitized IF signal, which are the I, Q, $-I$, and $-Q$ values. With this method, the I and Q values are obtained through sampling, and thus the analog circuit complexity is reduced.

We implemented digital beam measurement based on the 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

The SSRF is a third-generation light source. 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 $f_{\rm mc}$=693.964 kHz. Signals from the BPM pickups are high frequency pulses with a repetition frequency of 499.654 MHz ($f_{\rm mc}\times720$) and a pulse width of less than 200 ps [13], and the signal energy is located on the frequency of 499.654 MHz and its integral multiples in a frequency range beyond 10 GHz.

Shown in Fig. 5 is the structure of the beam position measurement electronics [20–23]. After amplification and band pass filtering, the RF signal is directly digitized by high-speed ADCs with a sampling frequency of 117.2799 MHz, through which a digital IF signal of 30.5344 MHz is obtained. Based on the IQ demodulation method, this IF signal is moved to DC (i.e. I and Q values are obtained) through a Digital Down Conversion (DDC) algorithm in the FPGA, as shown in Fig. 6. Then the amplitudes of four channels can be calculated, from which the position information can be finally obtained.

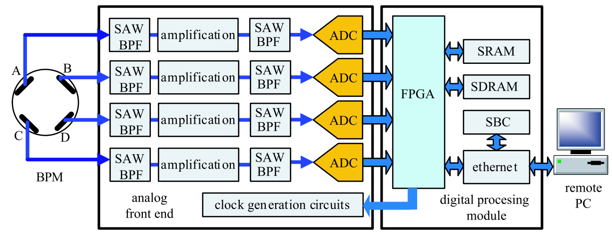

Fig. 5. (color online) Block diagram of the fully digital beam position measurement system.

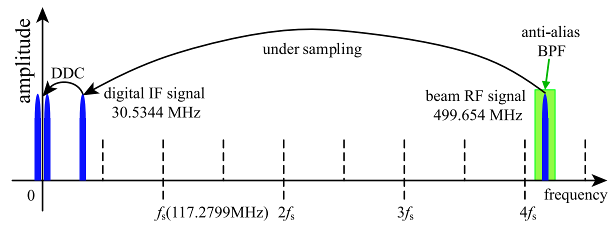

Fig. 6. (color online) Signal processing in the frequency domain.

The structure of the kernel digital signal processing algorithm is shown in Fig. 7. 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 Δ/Σ algorithm.

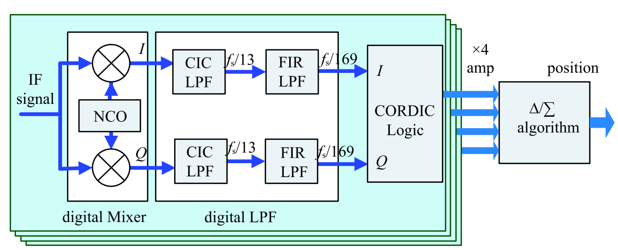

Fig. 7. (color online) Block diagram of the kernel digital signal processing algorithm.

A series of tests were conducted to evaluate the system performance both in the laboratory and with the beam in SSRF. Shown in Fig. 8 are the beam position measurement resolution test results, which indicate that the TBT position resolution is better than 10 μm (K_x = K_y=10 mm) within the input signal amplitude range from −40 dBm to 10 dBm.

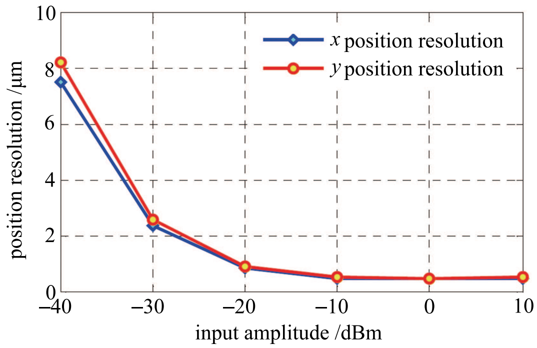

Fig. 8. (color online) Position resolution in x and y directions.

We also conducted tests on the Libera series of digital beam measurement instruments for performance comparison, as they are widely applied in accelerators around the world. Fig. 9 and Fig. 10 are the test results for the Libera Electron and its new version Brilliance.

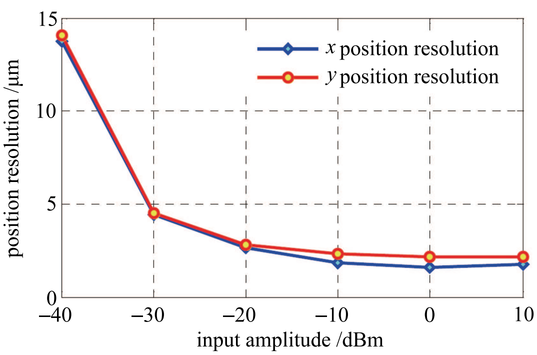

Fig. 9. (color online) Position resolution in x and y directions for Libera Electron.

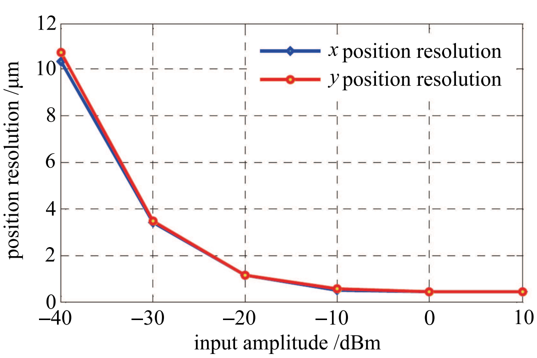

Fig. 10. (color online) Position resolution in x and y directions for Libera Brilliance.

Commissioning tests were also conducted at SSRF. Figure 11 and Fig. 12 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 are in good accordance with the beam behavior.

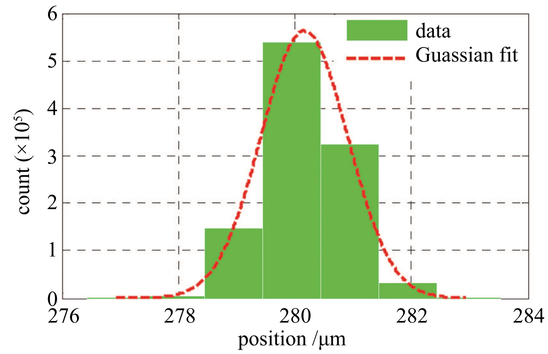

Fig. 11. (color online) Histogram of the y position measurement results.

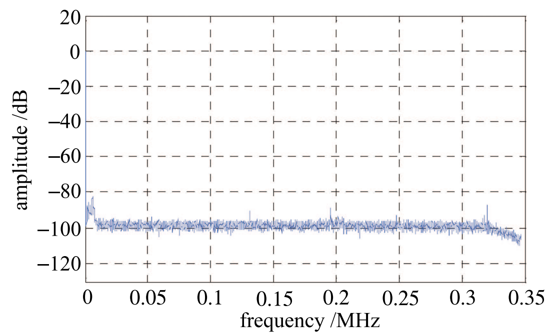

Fig. 12. (color online) Frequency spectrum of the y position measurement results.

We also conducted tests during the beam injection process. The results are shown in Fig. 13, in which the fluctuation can be clearly observed, as expected. Figure 14 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.

We have finished the design and testing of the electronics systems, and three such modules are now used at SSRF.

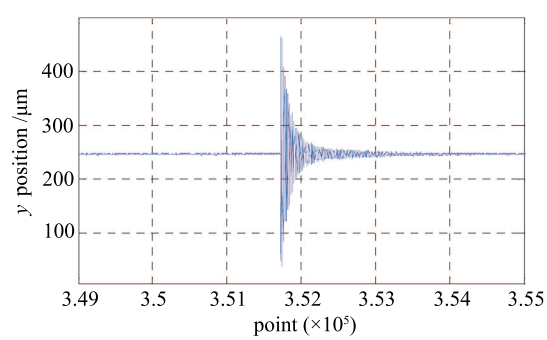

Fig. 13. (color online) Waveform of the y position measurement results during injection.

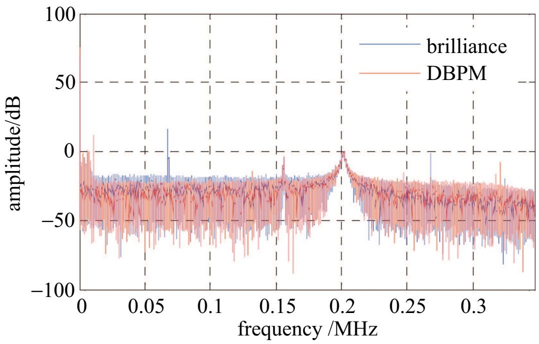

Fig. 14. (color online) Frequency spectrum of the y position measurement results during injection.

We recently performed further research on the system calibration and correction of the beam position measurement results. This is one important issue that needs to be addressed in order to put this instrument in real applications. There exist mismatches among different channels in the RF manipulation circuits as well as ADCs, and the mismatch coefficients vary with different input signal amplitudes; therefore, beam position measurement errors are inevitable. We conducted tests to obtain the calibration coefficient of the gain values of the four channels, and then implemented real-time correction algorithms in the FPGA with Look-Up Tables (LUTs). Shown in Fig. 15 are the beam position test results, which indicate that the position errors are greatly reduced by correction.

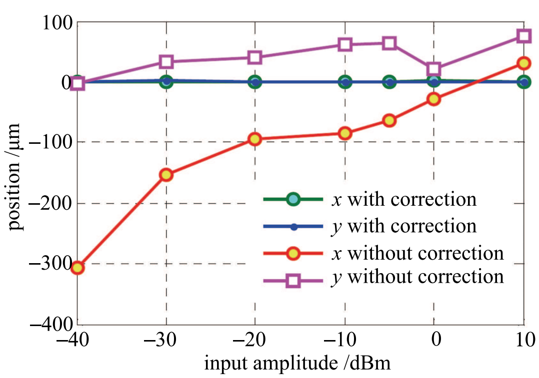

Fig. 15. (color online) Beam position test results with/without correction.

Besides, we are now also working on the bunch-by-bunch beam position feedback system design. We use 500 Msps 12 bit ADCs to digitize the beam bunch signals. With algorithms based on FIR filters integrated in one FPGA, feedback information is calculated and converted to analog signals through a 500 Msps DAC, which is then fed to kickers to make the beam bunches run in the optimal orbit along the SSRF storage ring. A prototype system is now in the R&D phase.

4 Digital beam phase and energy measurement system in CSNS drift tube linac

As shown in Fig. 16, the CSNS consists of an H^- ion source, Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL), Rapid Cycling Synchrotron (RCS) and target. To guarantee the beam quality in the DTL, the system we designed imports beam RF signals from Fast Current Transformers (FCTs) in the DTL, and then calculates 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 core task is beam phase measurement.

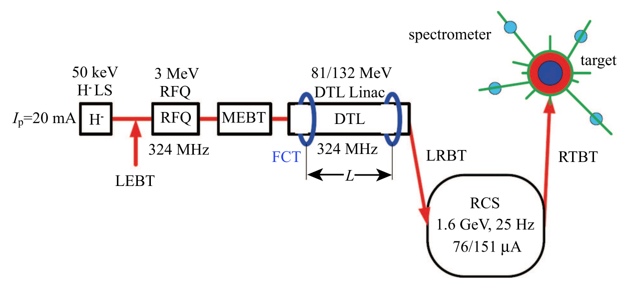

Fig. 16. (color online) Layout of CSNS.

Shown in Fig. 17 is the block diagram of this beam measurement system [24]. The input RF signal is filtered by a BPF, amplified, and then down converted to an IF signal through a mixer and LPF. Then this IF signal is digitized with a sampling frequency of four times the IF signal frequency, through which the I and Q arrays are obtained. Through the Digital Signal Processing (DSP) algorithms integrated in the FPGA, the beam phase information can be finally obtained.

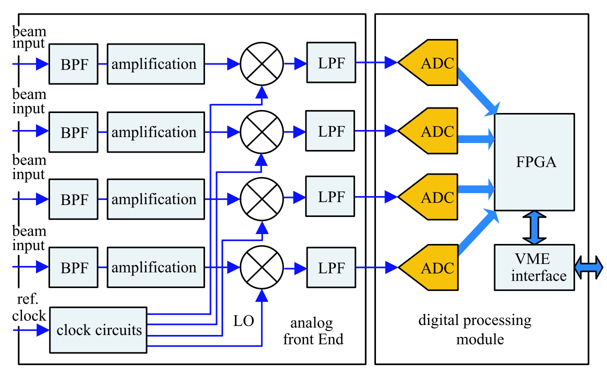

Fig. 17. (color online)Block diagram of the beam phase and energy measurement system.

The input beam signals are pulses with a repetition frequency of more than 300 MHz and a leading edge of 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].

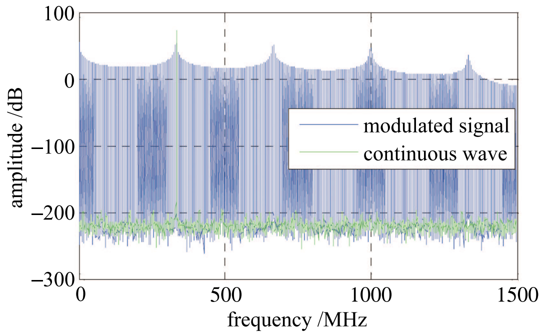

Fig. 18. (color online) Frequency spectrum of the modulated signal.

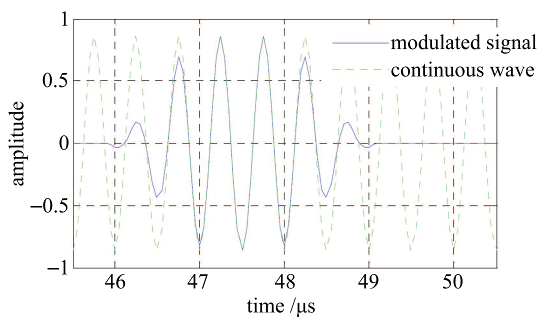

Fig. 19. (color online) Simulation results of the signal after down conversion.

As shown in Fig. 18, the frequency is quite complex (as marked in blue in Fig. 18), as expected. Shown in Fig. 19 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 verify the correctness of the signal processing method.

Since the IF signal contains exactly four samples in each period after A/D conversion, i.e. I, Q, $-I$, and $-Q$, we can calculate the beam phase based on DSP algorithms, which are integrated within one single FPGA, as shown in Fig. 20.

We also conducted tests to evaluate the system performance. Figure 21 and Fig. 22 are the test results of the waveform of the digitized IF signal, which indicate that there exist 4 samples in each period, as expected.

Figure 23 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°.

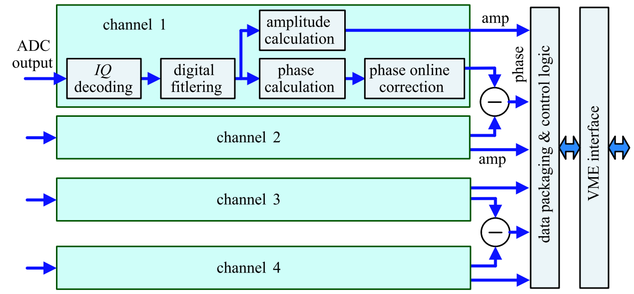

Fig. 20. (color online) Block diagram of DSP algorithms integrated in the FPGA.

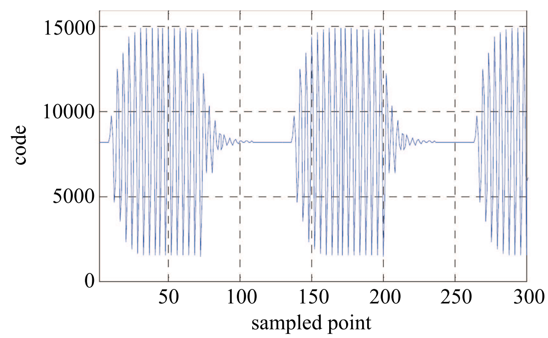

Fig. 21. (color online) Waveform of the digitized IF signal.

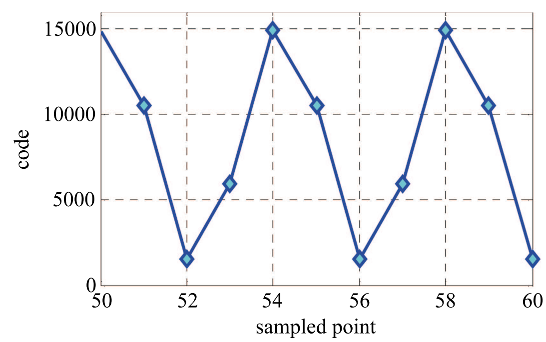

Fig. 22. (color online) Detailed waveform of the digitized IF signal.

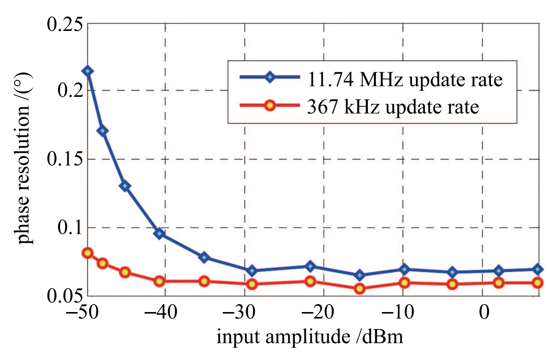

Fig. 23. (color online) Phase resolution test results.

Research was also performed on beam phase calibration and correction. As mentioned above, in the beam measurement of DTL in CSNS, the beam energy can be measured with the beam phase difference information between a pair of FCTs. The delay of the analog circuits in each channel changes with different input signal amplitudes (corresponding to different channel gain values), and it is found that when the gain of one channel changes, the delay of the adjacent channel is influenced, so phase correction in this system is quite complex. To solve this problem, we proposed to design a two-dimensional LUT. To guarantee a good phase calibration precision, we used Network Analyzer Agilent E5061A to measure the input signal phase difference, as shown in Fig. 24.

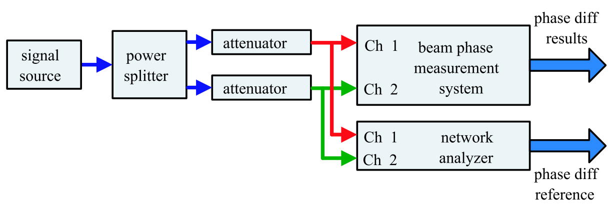

Fig. 24. (color online) Setup for phase calibration.

As shown in Fig. 24, we used the output of the network analyzer as a reference for the phase difference measurement results, and then the phase errors could be calculated. We changed the input signal amplitudes of the two channels separately, and we could then obtain two-dimensional phase difference calibration results, as shown in Fig. 25.

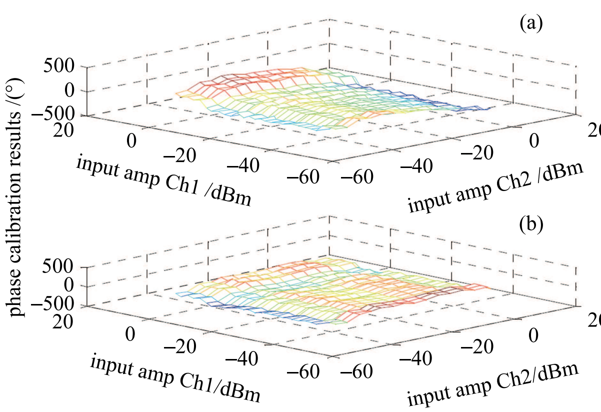

Fig. 25. (color online) Phase difference calibration results: (a) output of the beam measurement system; (b) output of the network analyzer.

With the calibration results in Fig. 25(a) and (b), we established the phase correction LUT based on the interpolation method, as shown in Fig. 26. This LUT can be easily integrated in FPGA devices to achieve real-time phase correction.

We also conducted tests to evaluate the effect of this correction method with the input amplitudes scattered over the range from −50 dBm to 7 dBm. Figure 27 shows the phase error test results before and after correction, which indicate that a phase correction precision better than 0.5° is achieved.

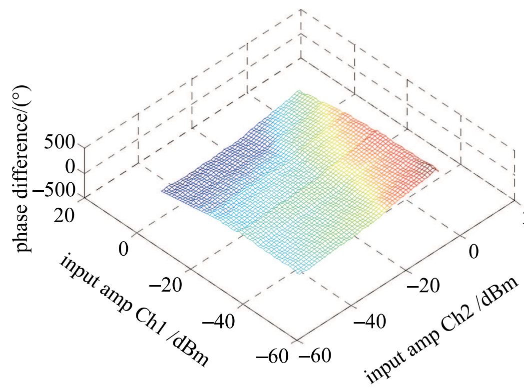

Fig. 26. (color online) Content of the two-dimensional phase correction LUT.

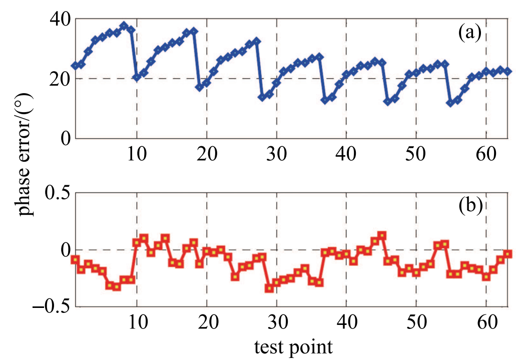

Fig. 27. (color online) Phase error test results (a) without correction and (b) with correction.

5 Digital Beam Phase and Position Measurement (BPPM) system in the ADS proton linac

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 undersampled. 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. 28.

Since the I and Q arrays are obtained directly through A/D conversion, compared with the above two systems, the 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 the ADS, and integrated both beam phase and position measurement within one single instrument.

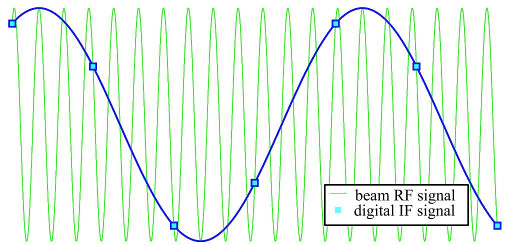

Fig. 28. (color online) Principle of the direct IQ under-sampling method.

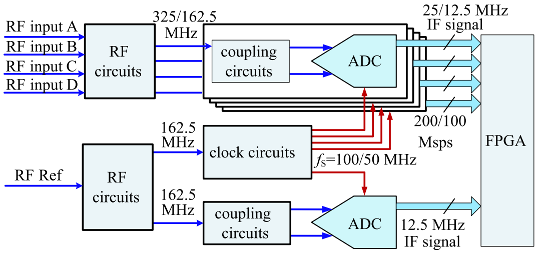

Fig. 29. (color online) Block diagram of the beam phase and position measurement system.

As shown in Fig. 29, 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

$$f_S = \frac{4f_{RF}}{4M \pm 1}, \tag{7}$$

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 agreement with (7).

Shown in Fig. 30 and Fig. 31 are the test results of the beam phase and position resolution. 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.

In this BPPM system, real-time calibration is also a great concern, especially for phase error correction. Because the signals are imported from the four electrodes of the BPM, these four signals are required to be summed together before phase calculation to eliminate phase dependence on beam position [27]. Since the beam signal is directly digitized using high-speed ADCs, we plan to conduct phase correction in the FPGA based on processing of the four digital IF signals before summation. This research is now underway.

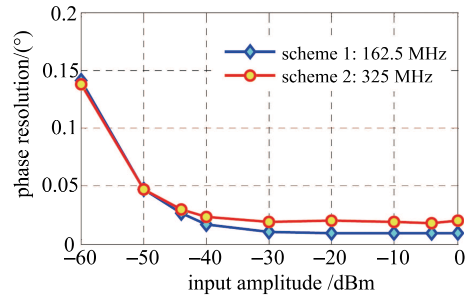

Fig. 30. (color online) Phase resolution test results.

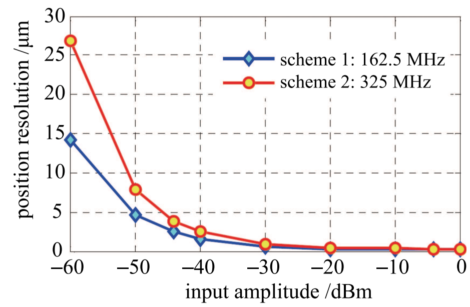

Fig. 31. (color online) Position resolution test results.

6 Discussion and summary

With the progress of high-speed high-resolution A/D conversion and digital signal processing techniques, fully digital beam diagnostics has become a research hot spot. New features of beam measurement systems are expected by employing modern electronics techniques, including:

1) Higher precision. Compared with traditional analog methods, modern digital beam measurement systems do not suffer from the noise, distortion, and mismatches introduced by analog circuits, so high measurement precision can be guaranteed. Further enhancement of precision is limited by the performance of A/D conversion circuits. Of course, high quality ADC chips are commercially available; however, the techniques needed to use these ADCs to achieve higher system-level performance is an important domain of research.

2) More functionality integrated in one single instrument. Since signal processing is implemented in the DSP domain, it makes it possible to integrate more functionality within one single instrument. For example, in the BPPM system designed for the ADS linac, both beam phase and position can be measured simultaneously. In the SSRF, based on high-speed A/D conversion techniques, it should also be possible to integrate the functionalities of turn-by-turn beam position measurement

and bunch-by-bunch beam position feedback within one instrument in future.

3) Versatile data interfaces for remote communication. Multiple interfaces, such as megabit Ethernet, USB and fiber transmission based gigabit Ethernet, are often integrated in modern beam measurement instruments. This makes it easy for users to communicate with these instruments from remote computers.

4) Higher density for system-level integration. This could be achieved through two approaches. One is system-level integration based on standard data bus and crates. For example, in the beam measurement systems in CSNS and ADS, VME and PXI standards are employed, respectively. Besides, in this way, the system scale can be easily extended according to application requirements. Another approach is miniaturization of electronics modules. This requires Printed Circuit Board (PCB) layout techniques to achieve both high density and good signal transmission quality (i.e. good signal integrity). One good example is the Libera Single Pass H series of instruments [19] designed by Instrumentation Technologies.

5) Precise automatic real-time correction. Based on logic design in FPGA devices, real-time correction can be achieved. New algorithms to achieve more efficient correction could be expected in future.

In this paper, we discussed modern digital beam measurement methods based on IQ analysis, and also presented three beam measurement electronics systems, 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 for future accelerators.

The authors would like to thank their collaborators in SINAP, IHEP, and IMP, CAS for their help, which has made this work possible.

References

1 J. Hinkson, J. Johnston, I. Ko, Advanced Light Source (ALS) Beam Position Monitor, *Proc. Particle Accelerator Conf.*, **3**: 1507-1509 (1989)

2 J. Y. Huang, D. H. Jung, D. T. Kim et al, PLS Beam Position Monitoring System, *3rd European Particle Accelerator Conference*, Berlin, Germany, 1992, p. 1115-1117

3 W. H. Hwang, H. G. Kim, W. W. Lee et al, Measurement of Beam Energy Drift in PLS 2.5 GeV LINAC, *3rd Asian Particle Accelerator Conference*, Gyeongju, Korea, 2004, p. 300-302

4 P. Gu, Z. Geng, G. Pei et al, RF phasing system for BEPCII LINAC, *3rd Asian Particle Accelerator Conference*, Gyeongju, Korea, 2004, p. 288-290

5 Z. Geng, P. Gu, M. Hou et al, Design and calibration of a phase and amplitude detector, *Proc. Particle Accelerator Conf.*, Knoxville, Tennessee, 2005, p. 1-3

6 J. Yue L. Ma, J. Cao, L. Wang, High Power Laser and Particle Beams, **17**(6): 951-955(2005)

7 J. Power, M. Stettler, The Design and Initial Testing of a Beam Phase and Energy Measurement for LEDA, *Proceeding of the 1998 Beam Instrumentation Workshop (BIW98) conference*, 1978

8 Masanori Ikegami et al, RF Tuning Schemes for J-PARC DTL and SDTL. Proceedings of LINAC 2004, Lübeck, Germany, p. 414-416

9 J. F. Power, J. D. Gilpatrick, M. W. Stettler, Design of A VXI Module for Beam Phase and Energy Measurements for LEDA, *Proceedings of the Particle Accelerator Conference*, **2**: 2041-2043(1997)

10 J. Power, J. O'Hara, S. Kurennoy, M. Plum, M. Stettler, Beam position monitors for the SNS LINAC, *Proc. Particle Accelerator Conf.*, **2**: 1375-1377(2001)

11 HaraldKlingbeil. A Fast DSP-Based Phase-Detector for Closed-Loop RF Control in Synchrotrons. IEEE Trans. Instrum. Meas., **54**: 1209-1213(2005)

12 LAI Long-Wei, LENG Yong-Bin, YAN Yin-Bing et al, Nuclear Techniques, **33**(10): 734-739(2010)

13 YI Xing, LENG Yong-Bin, LAI Long-Wei et al, Nuclear Science and Techniques, **22**(2): 65-69(2011)

14 SUN Bao-Gen, WANG Jun-Hua, LU Ping et al, Journal of University of Science and Technology of China, **37**(4-5): 364-370(2007)

15 SUN Bao-Gen, CAO Yong, Li Ji-Hao et al, Journal of University of Science and Technology of China, **37**(4-5): 475-482(2007)

16 YU Lu-Yang, YIN Chong-Xian, LIU De-Kang, Nuclear Science and Techniques, **16**(2): 76-81(2005)

17 C.X. Yin, D.K. Liu, L.Y. Yu, Digital Phase Control System For SSRF LINAC, *Proceedings of ICALEPCS07*, 2007, p.717-719

18 A. Kosicek, Libera electron beam position processor, *Proceedings of the 2005 Particle Accelerator Conference*, IEEE, 2005: 4284-4286

19 Libera Single Pass H specification, Instrumentation Technologies

20 Han Yan, Lei Zhao, Shubin Liu, Kai Chen, Weihao Wu, Qi An, YongbinLeng, Xing Yi, Yingbing Yan, Longwei Lai, Nuclear Science and Techniques, **23**: 75-82 (2012)

21 CHEN Kai, LIU Shubin, YAN Han, WU Weihao, ZHAO Lei, AN Qi, LENG Yongbin, YI Xing,YANYingbing, LAI Longwei, Nuclear Science and Techniques, **22**(4): 193-199 (2011)

22 Han Yan, Shubin Liu, Kai Chen, Weihao Wu, Lei Zhao, Qi An, YongbinLeng, Xing Yi, Yingbing Yan, Longwei Lai, The Design and Initial Testing of the Beam Position Measurement System in SSRF Based on Fully Digital Signal Processing, *International Workshop on ADC Modeling, Testing and Data Converter Analysis and Design and IEEE 2011 ADC Forum*, Orvieto, Italy, June 30th - July 1st, 2011

23 Hao Zhou, Shubin Liu, Kai Chen, Weihao Wu, Lei Zhao, Qi An. Design of the Fully Digital Beam Position Monitor for Beam Position Measurement in SSRF, *9th International Conference on Electronic Measurement and Instruments*, **1**: 1045-1051 (2009)

24 Lei Zhao, Shubin Liu, Shaochun Tang, Qi An, IEEE Transactions on Nuclear Science, **57**(2): 533-538 (2010)

25 ZHAO Lei, LIU Shu-Bin, AN Qi, Nuclear Electronics & Detection Technology, **29**(5):1005-1011 (2009) (in Chinese)

26 Lei Zhao, XingshunGao, Xiaofang Hu, Shubin Liu, Qi An, IEEE Transactions on Nuclear Science, **61**(1): 538-545 (2014)

27 S.S. Kurennoy, Beam Phase Detectors for Spallation Neutron Source LINAC, *Proceedings of EPAC 2000*, Vienna, Austria, p. 1765-1767