Development of an integrated four-channel fast avalanche-photodiode detector system with nanosecond time resolution

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Abstract: A four-channel nanosecond time-resolved avalanche-photodiode (APD) detector system is developed at Beijing Synchrotron Radiation Facility and the detector system is tested using a single channel for the four-channel system. The detector system consists of three parts: i) four APD sensors, ii) four fast preamplifiers and iii) a time-digital-converter (TDC) readout electronics. The C30703FH silicon APD chips fabricated by Excelitas are used as the sensors of the detectors. It has an effective light-sensitive area of 10 × 10 mm² and an absorption layer thickness of 110μm. A fast preamplifier with a gain of 59 dB and bandwidth of 2 GHz is designed to readout of the weak signal from the C30703FH APD. The TDC is realized by a Spartan-6 field-programmable-gate-array (FPGA) with multiphase method in a resolution of 1ns. The arrival time of all scattering events between two start triggers can be recorded by the TDC. The detector has been used for nuclear resonant scattering study at both Advanced Photon Source and also at Beijing Synchrotron Radiation Facility. For the X-ray energy of 14.4 keV, the time resolution, the full width of half maximum (FWHM) of the detector (APD sensor + fast amplifier) is 0.86 ns, and the whole detector system (APD sensors + fast amplifiers + TDC readout electronics) achieves a time resolution of 1.4 ns.

Key words: HEPS-TF, nanosecond time resolution, APD, fast amplifier, TDC

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1. Introduction

The silicon avalanche-photodiode (APD) detector system has a number of unique features for X-ray applications such as high counting rate of 10^7, large dynamic range of 10^9, sub-nanosecond time resolution, and very low dark counting rate at mHz. It has been widely used in time-resolved experiments, such as nuclear resonant scattering (NRS) with synchrotron radiation [1]. In the NRS experiment [2-4], a strong electronic scattering from the sample occurs promptly on a ps time scale after the incident pulse, while the nuclear resonant scattering is delayed on a 10's of ns time scale by the finite lifetime of the excited state which carry from ns to us. Therefore, one can separate the nuclear delayed events from the electronic scattering ones. The detailed time structure of the nuclear resonant scattering can be measured by a nanosecond time-resolved APD detector system presented here.

The High Energy Photon Source-Test Facility (HEPS-TF) is an R&D project for the planned future High Energy Photon Source (HEPS) in Beijing, China. Development of an APD detector system is a

R&D program for the NRS-type of experiments at the new light source. Furthermore, a good APD system can also be used in other experiment, such as the laser pump / X-ray probe experiments, storage ring electron bunch structure and bunch-purity measurements.

Time-resolved APD detector systems have been reported before by several research groups [5-10]. The APD reported by SPring-8 and KEK are based primarily on silicon sensors fabricated by Hamamatsu Photonics. The APD sensors manufactured by Excelitas are usually adopted by ESRF and APS. Those detector systems have a time resolution between 0.1 ns and 1.7 ns depending on the thickness of chips. However, the time measurement electronics of those traditional detector systems was based on the NIM-modules, which can only record the time of the first delayed nuclear scattering event between two start triggers. Moreover, the NIM-module readout electronics has a low integration and is cumbersome for multiple APD detector system or APD array detector system in the future.

In this paper, we have developed a highly integrated APD detector system for NRS experiment. We can realize four-channel TDC readout using Spartan-6 XC6SLX100T chip. The implemented detector system has four APD sensors, four fast preamplifiers, and a time-to-digital convert (TDC) readout electronics. In order to gain sufficient signal-to-noise ratio to detect a single photon, the fast preamplifier with three cascaded amplification stages is designed to readout the weak signal from APD sensor . The TDC readout electronics integrates the NIM-modules functions into one printed circuit board (PCB). The time measurement is based on field programmable gate array (FPGA) TDC, which can record the time of all scattering events between two start triggers. Compared to the current NIM-module, this work mode could record all the photons and improve the experiments efficiency. The detailed design of the developed detector system is discussed in the following sections. The measurement results tested using a single channel for the four-channel system are also presented to demonstrate the capability of the detector system.

2. Design of a nanosecond time-resolved APD detector system

The practical goal of the designed APD detector system is defined to accomplish the ^{57}Fe NRS experiment at a synchrotron radiation beamline. The X-ray energy of ^{57}Fe nuclear resonance is 14.4 keV, while the lifetime of this radiation is 141 ns. The targeted efficiency of the APD detector system is larger than 10 % at 14.4 keV, and the count rate should be larger than 10^6 photons/s. Since the detector must recover quickly to record a nuclear scattering event a few 10's ns later, the output pulse width at base of the preamplifier should be less than 20ns. In some experiments the nuclear resonant scattering event may be as low as 0.1 Hz, so the dark count rate of our detector system is designed to be as low as 0.01 Hz. In addition, the time resolution of < 2 ns is also needed to capture the arrival time of scattering events accurately. The design specification is summarized in Table 1. The simultaneous requirement of high efficiency, high counting rate, fast recovery time, and very low dark counting rate is very challenging in the detector system design.

Fig.1 shows the implemented four-channel APD detector system diagram. Each detector consists of an APD sensor and a fast preamplifier. A TDC readout electronics handles four readout channels. Each readout channel can accomplish the functions of signal inversion, discrimination and TDC. The time data, obtained by the TDC readout electronics, is transmitted to a data acquisition (DAQ) unit via a single optical fiber.

Table1 Design specification of the implemented APD detector system

Parameter	Requirement
Efficiency	> 10 %
Count rate	> 1 MHz
Output pulse width of the pre-amplifier	<
Dark counting rate	< 0.01 Hz
Time resolution	< 2 ns

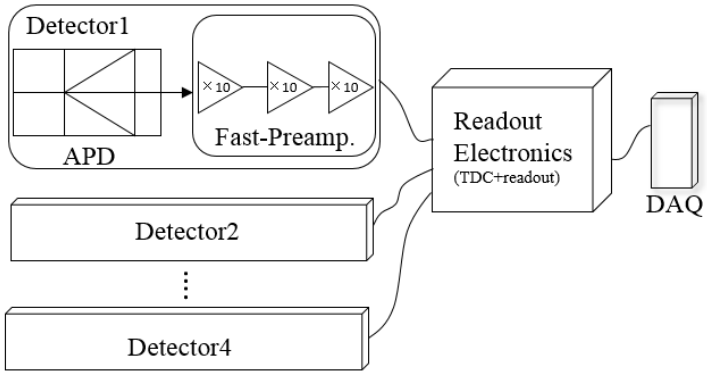

Fig. 1. Structure of the detector system

2.1 Si-APD sensor

The APD sensor used in this detector system is C30703FH which is fabricated by Excelitas Technologies. The sensor is designed on a 120 μm thick silicon wafer with reach-through structure [11]. The avalanche amplification region located on the back of the device is very narrow, so the device presents an absorption layer thickness about 110 μm. This absorption thickness makes the sensor calculated efficiency 25 % at the energy of 14.4 keV. The APD gain is about 50-100 when the high voltage is set from 300V-400V. The sensitive area of this sensor is 10 × 10 mm^2, which provides a sufficient solid angle for inelastically scattered X-ray detection.

2.2 Fast preamplifier

The current signals from the APD are processed by a high bandwidth 2 GHz, high gain 59 dB preamplifier. The schematic diagram of the fast preamplifier is shown in Fig. 2. The preamplifier consists of three Mini circuits Mar6+ commercial amplifier chips and two π-type resistant networks. These amplifier chips are cascaded in three stages to get a gain of about 60 dB. To increase the stability of the preamplifier, the π-type resistant networks are added between two amplifier chips, and they are designed with individual components.

The input impedance of the π-type resistant networks should be matched with the output impedance of the signal, and the output impedance of the π-type resistant networks should be matched with the load.

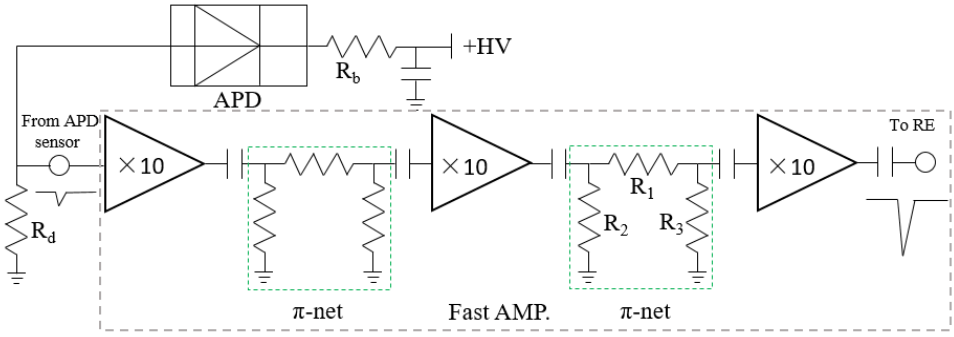

Fig. 2. Schematic of the fast preamplifier. R_b limits the bias current and R_d is closed to the bias circuit. The pulse of the fast signal from APD capacitive coupled to the first stage amplifier

The calculation of networks is shown in the formula below

$$Z_{in} = R_2 \,\mathrm{P}\left(R_1 + R_3 \,\mathrm{P}\, 50\Omega\right) = 50\Omega$$

Here, the values of the resistances are R_1 = 10 Ω， $R_2 = R_3$ = 300 Ω. The attenuation for one π-type networks is 0.28 dB. Since the gain of the commercial amplifier chip is 20 dB, the preamplifier has a gain of 59 dB.

The fast preamplifier is first designed and fabricated on a printed circuit board. The preamplifier board is sitting in an aluminium box to shield the environmental electromagnetic radiation. Furthermore, the high voltage circuit of the APD sensor is isolated from the fast preamplifier by an aluminium wall in the box. Therefore, the high voltage circuit will not induce noise to the fast preamplifier. Through the above measures, a stable preamplifier with high bandwidth and high gain is implemented. The fast preamplifier with APD sensor is shown in Fig.3.

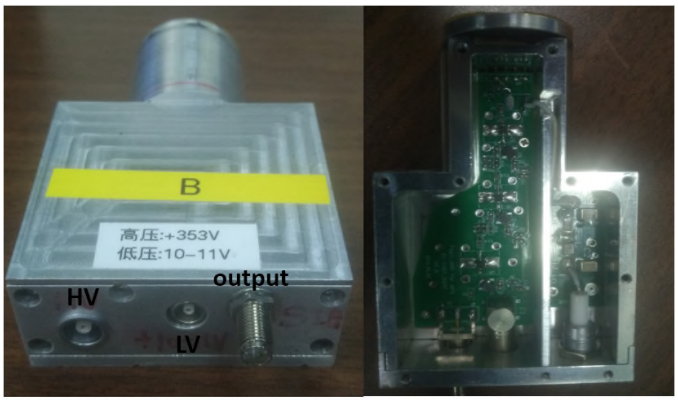

Fig.3 The real picture of the preamplifier sitting in the box with high voltage and signal separated

2.3 TDC readout electronics

Compared to the NIM-module TDC, the FPGA TDC we designed is much more integrated and it can used in multi-element or array APD detector system in the future. Fig. 4 shows the logic diagram of the time measurement for NRS experiment. The timing signal is the RF signal from the storage ring and it works as the start signal of the TDC. A prompt and a delayed signal work as the stop signal of the TDC. The time, defined as the time difference between the start signal and the stop signal, is measured by the

TDC. In our system, the TDC readout electronics can measure one or more scattering events after the start signal, which is an advantage over the current NIM-module used in NRS.

Fig. 5 shows the structure of one channel TDC. Signals from the fast preamplifier are modulated by the stage A1, which magnifies the signal several times and changes the polarity of the signal from negative to positive, so that the signal can be detected by the discriminator (TH). A digital-to-analogue converter (DAC) is added to adjust the discrimination threshold. Then the time between the start signal and the stop signal is measured by the FPGA TDC.

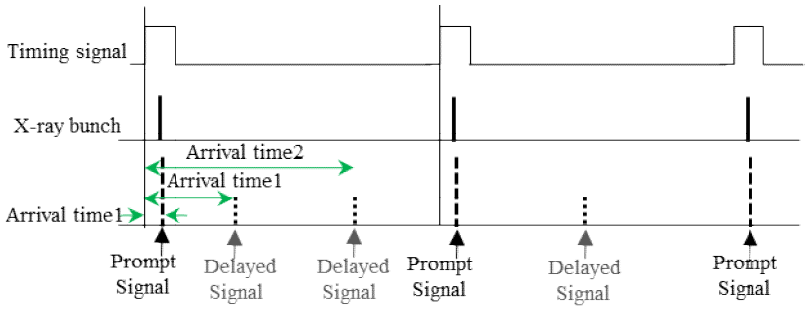

Fig. 4. Logic diagram of the time measurement for NRS experiment

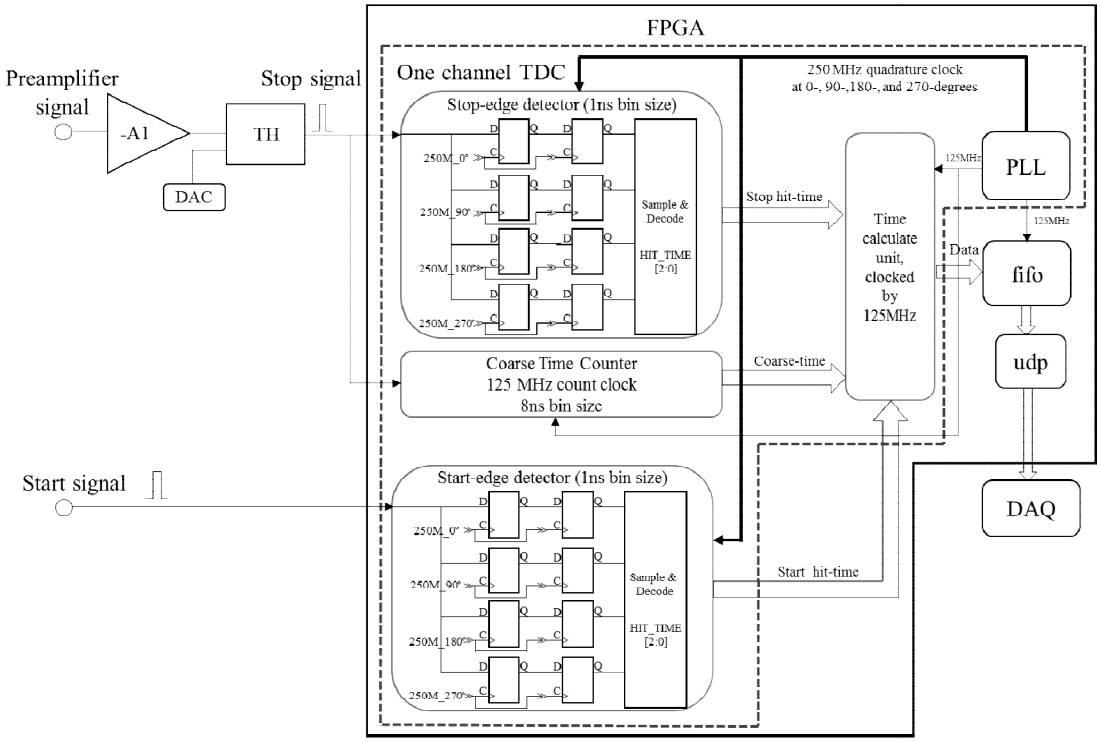

Fig. 5. Structure for one channel of the TDC readout electronics

The TDC uses a multi-phase technology and is realized in an FPGA Spartan-6 XC6SLX100T chip [12]. It consists of a stop-edge detector, a shared start-edge detector, a coarse-time counter, a time-calculation unit, and a shared phase lock loop (PLL). The PLL creates a 250 MHz quadrature clock with 0-, 90-, 180-, and 270-degrees shifts for the stop edge detector and the shared start-edge detector. The PLL also generates a 125 MHz clock for the coarse-time counter. Each phase of the quadrature clock operates at 250 MHz, essentially creating a clock that operates at 1 GHz. The

stop-edge detector detects the rising edge of the stop signal and records the stop hit-time in every period of 8 ns. The quadrature clock makes the equivalent to of a 1 GHz clock, and the resolution size of the stop-edge detector is 1ns. The start-edge detector records the start hit-time using the same working principle as the stop-edge detector. The coarse-time counter counts at a count clock of 125 MHz, with a period of 8 ns. The time calculation unit calculates the time by combining the start hit-time, stop hit-time and the coarse-time. The timing diagram of the TDC is simply illustrated in Fig. 6, and the time = start hit-time + coarse-time + stop hit-time, with a fixed time-stamp resolution of 1 ns per bin. The dead time of the TDC for each event is about 30ns for the spending of the time calculation. Then, the data of the arrival time are output through the first-in first-out (FIFO) buffer and the user datagram protocol (UDP) to the data acquisition (DAQ) system.

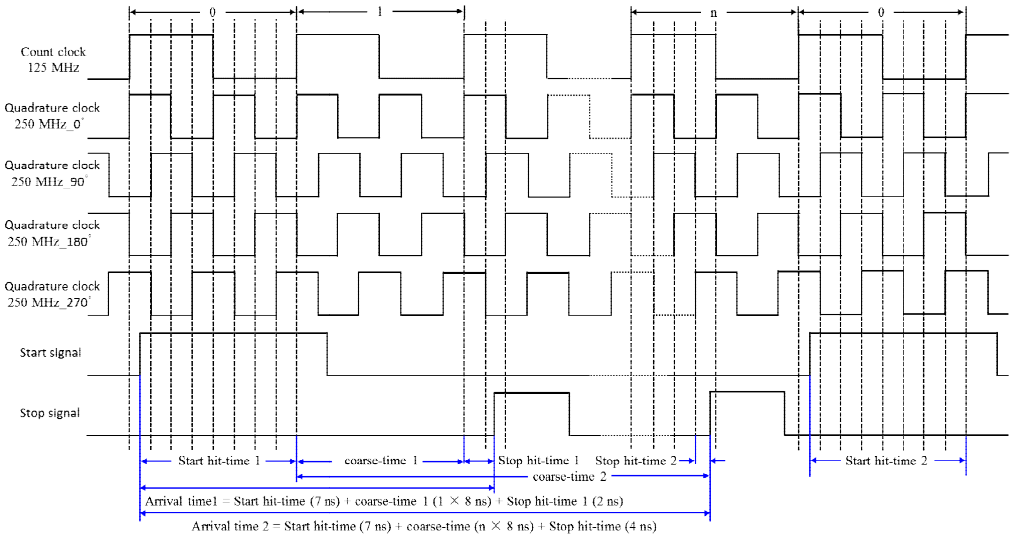

Fig. 6. Timing diagram of the TDC

Using the Spartan-6 XC6SLX100T chip, in order to meet the sequential relationship, four channel TDC could be designed in the limiting case. The TDC's scalable time range is from 1ns to 4096ns with 1ns bin. The TDC readout electronics is shown in Fig.7. The PCB size is

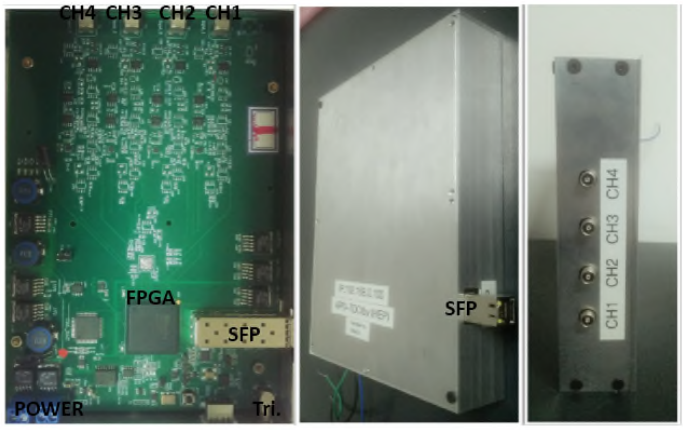

Fig.7 The picture of real TDC PCB board.

3. Performance

3.1 APD detector performance

The APD sensor and the fast preamplifier are housed in an aluminium box and tested as an X-ray detector at 1W2B experiment station of Beijing Synchrotron Radiation Facility (BSRF). The output pulse from the detector is shown in Fig. 8 (a), the output signal height is about 150mV when the photon enegy is 14.4keV, and the pulse width at base is about 25 ns. In order to estimate the count rate, the APD detector linearity at high count rate was investigated. The measured counting rate versus the input X-ray intensity monitored by the ion chamber and represented using ion chamber output voltage is shown in Fig. 8 (b). From the result, one can see that the detector has a good linearity below the count rate of 8-10 MHz. The dark counting mainly comes from the cosmic ray, by setting the threshold half of the pulse height (75mV), the dark counting rate is less than 0.01Hz.

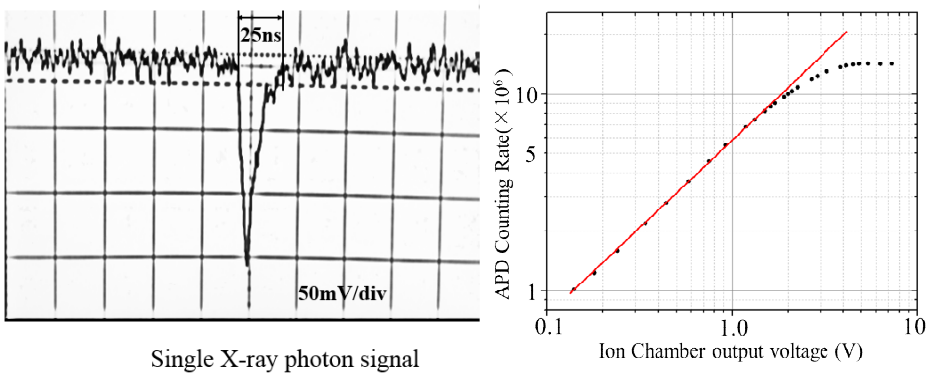

Fig. 8. (a) Single X-ray photon signal pulse, (b) Counting rate vs Ion Chamber output voltage

The time resolution of the designed APD detector is also investigated by measuring the arrival ti me of the X-ray photon after the locked RF signal from the accelerator storage ring. The FWHM time resolution of the detector is 860 ps with the threshold of 75mV (@14.4 keV), as shown in Fig. 9.

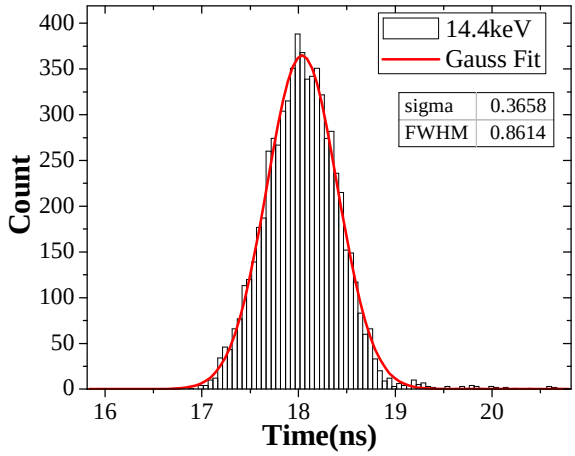

Fig. 9. Time resolution of the APD detector

3.2 TDC readout electronics performance

In the TDC readout electronics test, the threshold is set at half amplitude of the inverting buffer output swing. The resolution of TDC readout electronics is tested by using a high precision signal generator. Fig. 10 shows the time resolution of TDC in different situations: the integer input delta time and the input delta time with a decimal part of 0.5. The results indicate that the FWHM resolution is about 1ns, even in the worst input delta time case.

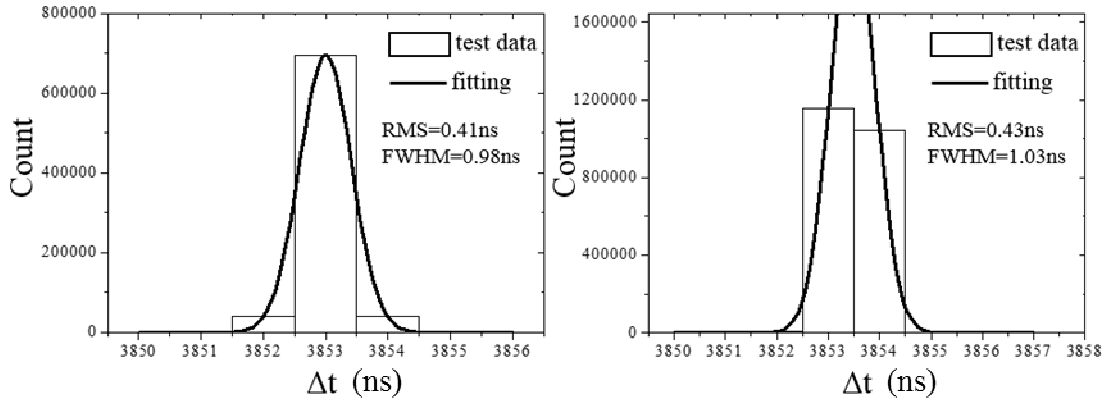

Fig. 10. (a) Time resolution of TDC electronics when the input delta time is 3853 ns; (b) time resolution of TDC electronics when the input delta time is 3853.5 ns

3.3 Time resolution of the detector system

This APD detector system is further tested at 1W2B experiment station of BSRF. In the test, the RF signal from the accelerator storage ring serves as a start signal of the TDC and the X-ray photon signals are the stop triggers for the TDC. Fig.11 shows the real connection of the system, the APD detectors with preamplifiers were connected to the TDC. In the test results, we use one of the four channels to verify the time resolution of the system.

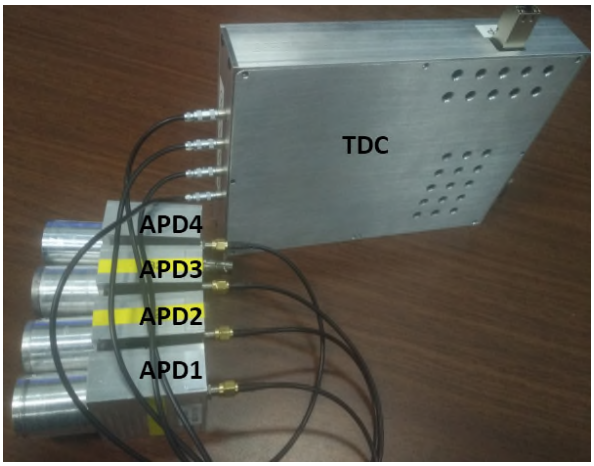

Fig.11 The APD detector system both with APD and TDC

Fig. 12 shows the measured time structure of the electron beam bunch of BSRF by using the developed APD detector system. The maximum count rate for each channel is 10MHz, which is limited by the APD signal pulse width, the synchrotron bunch mode and the data transfer. The electron beam bunch structure has a hybrid fill pattern in which a specific single bunch is filled with sufficient interval from other bunches. Fig. 13 shows the measured time resolution of the detector system at 14.4 keV and the overall time resolution FWHM is 1.4 ns.

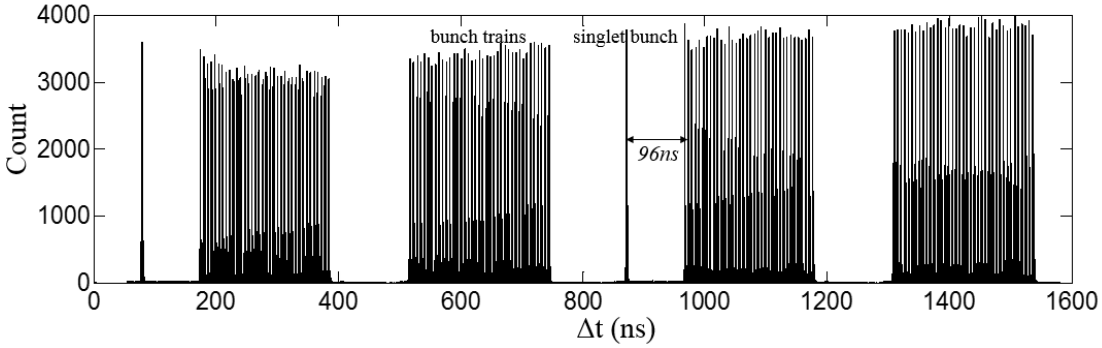

Fig. 12. Time structure of the beam bunch at BSRF: hybrid bunch structure with a singlet bunch. The interval between the singlet bunch and the bunch trains is about 96 ns

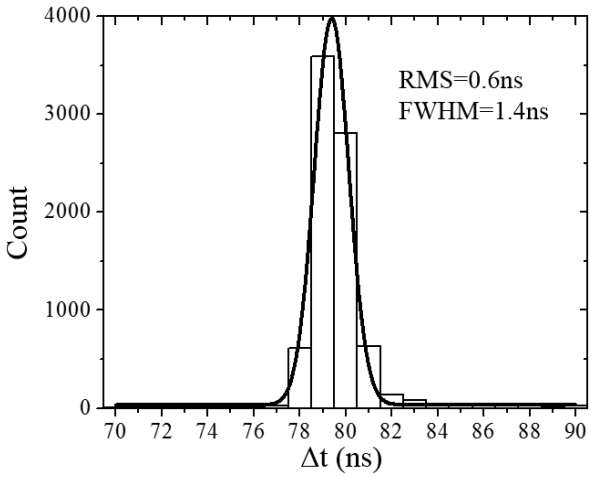

Fig. 13. Time resolution of the APD detector system

The designed detector system was employed for the nuclear resonant scattering experiments of samples at 3-ID beamline, Advanced Photon Source. In this experiment, the synchrotron Mössbauer spectra in time domain were collected with acceptable signal-to-noise ratio. Fig.14 shows the results of the experiment data. We use four APD detectors to detect the nuclear resonant scattered photons and the four channels could collect the photon time data at the same time, showing the same results in agreement with conventional Mössbauer spectroscopy. Therefore, we can improve the experiments efficiency if we use more APD detectors in the future.

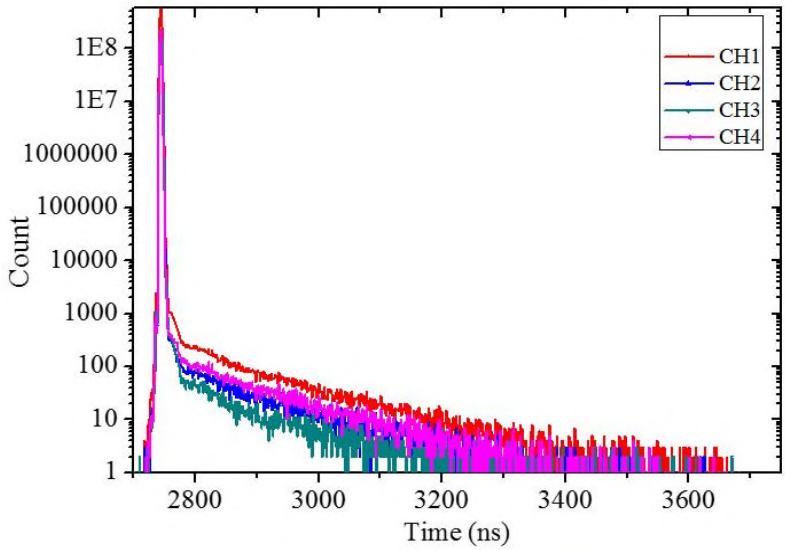

Fig. ^{57}Fe nuclear scattering experimental results with the designed detector system (Data taken at 3-ID Beamline of the Advanced Photon Source, USA).

4. Conclusions

We have developed an integrated four-channel nanosecond time-resolved APD detector system based on single element APD sensor. It can be used for NRS experiments in HEPS-TF project. In the future, the multi-element or array APD detector system will be designed using this four-channel TDC readout electronics. The effective light-sensitive area of 10 × 10 mm^2 and the efficiency of 25% @ 14.4 keV X-ray photons are achieved by utilizing the C30703FH silicon APD chips as the detector sensor. The fast preamplifier is designed on the discrete components with gain of 59 dB and bandwidth of 2 GHz. The TDC, with a resolution of 1ns, is realized by FPGA with multiphase method, which can record the time of all scattering events between two start signals. However, the existing NIM module system could only record one photon time between two start signals. The measured results indicate that the APD detector system time resolution is 1.4 ns. This novel APD detector system can be used for the nuclear resonant scattering technique, as well as pump/probe time-resolved experiment in the current synchrotron radiation facilities. It will also greatly promote the development of the NRS program in the future High Energy Photon Source in China.

Acknowledgements

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