A precise time measurement evaluation board for a radiography system of high-*Z* materials

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Abstract The time resolution of a radiography system for high-*Z* materials shall be at least 1 ns, hence the need of a time measurement system with a resolution of about 100 ps. In this paper, a Time Measurement Evaluation Board (TMEB) is developed to meet the need. It is based on the time-to-digital converter of ACAM TDC-GP2. Test results show an overall time resolution of 81 ps in detecting cosmic-rays with a plastic scintillator.

Key words Radiography, Time measurement, TDC, CFD, Resolution, Linearity

1 Introduction

Objects made of high-*Z* material such as uranium and other nuclear materials may be smuggled, but the shielding they cannot be detected standard radiation monitors[1]. Radiography of high-*Z* material using cosmic muons is a novel technology for detecting an object of high-*Z* materials and discriminating it from low-Z background materials. This is important for *nuclear material monitoring*. When cosmic muons penetrate an object, they undergo multiple Coulomb scattering, and the scattering depends on atomic number *Z* and density of a material. By measuring the multiple scattering angles, one is able to detect and image an object containing high-*Z* materials, in a nondestructive way[2-4]. Accurate determination of the scattering angle is of importance in the radiography, which requests a muon tracking detector of high position resolution, such as a system of drift chambers, and an electronic system of high time resolution.

Cosmic muons leave a trace of electrons as they pass through a drift chamber. Precise measurement of the electron drift time determines the hit position, which can be used to create a visual image of high-*Z* materials by reconstructing the muon tracks. The electronic system is a crucial component in resolving the signal output from the drift chamber. We have developed a time measurement evaluation board (TMEB) that meets electronics requirements of such radiography systems. In this paper, we report designs of the detector and TMEB, and present the test results.

2 Detector

Each of the drift chambers has three rows of sense wires. The upper and lower rows have nine sense wires each, while the middle row has eight sense wires. Between two neighboring sense wires, a field wire is arranged, so as to control the gas gain, and to reduce crosstalk between the sense wires and electrostatic deflection. The sense wires are of Φ30 µm gold-plated tungsten wires, and the field wires are of Φ100 µm gold-plated molybdenum wires. A typical wire cell structure is shown in Fig.1.

The hitting position is determined by two drift chambers with orthogonal wiring. The TMEB measures the time between the trigger signal and wire signal. This measured interval is the actual drift time plus an offset; which can be calibrated by data processing. Thus the hit position are determined according to the drift time[5].

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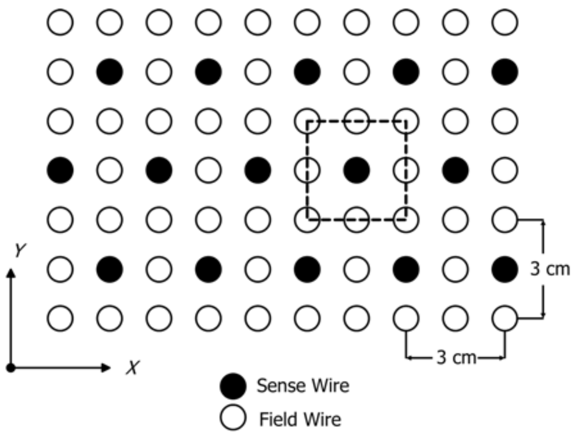

Fig.1 Structure of a typical wire cell in the drift chamber.

The time resolution can be related to position resolution of a radiograph system. Assuming a desired position resolution of 50 μm and a typical average drift velocity of 50 μm/ns, the TMEB that contributes no more than 10% of overall time resolution of the radiograph will achieve a time resolution of less than 100 ps.

3 TMEB

Structure of the TMEB is illustrated in Fig.2. The start signal is given by the drift chamber and the stop signal by the plastic scintillator detector. After a fast amplifier, the start signal goes through a constant fraction discriminator (CFD). The start and stop signals enter the TDC-GP2, and TDC output is transferred to the computer through a USB interface (CY7C68013).

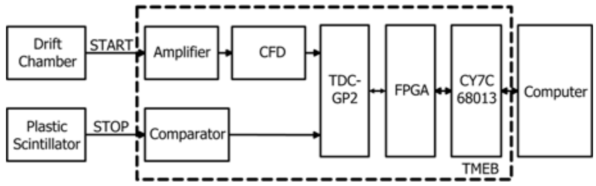

Fig.2 Block diagram of the TMEB.

3.1 CFD circuit

The TMEB time resolution σ_T is contributed by the TDC-GP2 time resolution $\sigma_G \approx 65$ ps[6] and the root mean square of time walk σ_C. Then, our objective of $\sigma_T \approx 100$ ps requests a σ_C of ≈75 ps. The time walk, which is caused by amplitude variation in the input signal[7], can be reduced by the CFD. Fig.3 shows the CFD design.

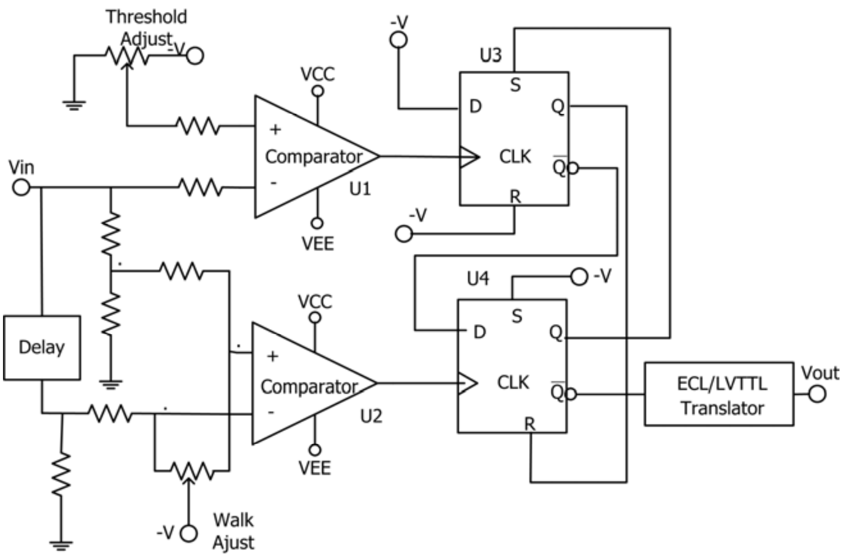

Fig.3 Schematics of the CFD circuit.

The circuit consists of the pre-discriminator (Comparator U1), constant fraction discriminator (Comparator U2), and output shaping unit. Emitter-coupled logic (ECL) components are used in the circuit because of their high speed.

While adjusting threshold of the pre-discriminator eliminates noise in the input signal, the constant fraction discriminator works as follows. The input signal is split into two signals, one is sent to the non-inverting terminal of U2 through an attenuation network, and the other is sent to the inverting terminal of U2 through a delay line. The output signal jitter of U2 can be reduced by adjusting the voltage difference between the two terminals. The output shaping is achieved by flip-flops. After the signal passes through the shaping unit, it is converted into a low voltage transistor-transistor logic (LVTTL) level by an ECL/LVTTL translator.

The signal delay in the CFD circuit is realized by serpentine routing. This delay is determined according to the rise time of the drift chamber signal. The zero-crossing position of the timing signal is determined by a fixed length of line.

3.2 TDC-GP2

TDC-GP2 is the new generation of ACAM general purpose TDCs. In one measurement mode, the two stop channels of TDC-GP2 refer to one start channel. Each channel has a typical 50 ps RMS resolution in a measurement range of 3.5 ns to 1.8 µs. Each input can be made sensitive to the rising edge, the falling edge, or both edges. The input signal of TDC-GP2 is required to be an LVTTL level so that the output of the CFD can be directly input into the TDC-GP2.

Prior to measurement, the TDC-GP2 must be configured, and then initialized so as to accept the start and stop signals. This is done by sending OPCODE “Init”. The TDC-GP2 will run until either the preset number of events is reached or a timeout occurs at the end of measurement range, where the TDC-GP2 starts to process the data according to the settings, and transfers the result to the output register. Finally, the data are read once the OPCODE “Read” is sent.

3.3 FPGA firmware

The TMEB is controlled with a field programmable gate array (FPGA) of EP1C6T144C8 (Altera Cyclone) used for data transmission and command explanation. As shown in Fig.4, the main function module inside the FPGA includes four parts: TDC configuration, the data receiver, control logic, and the USB interface.

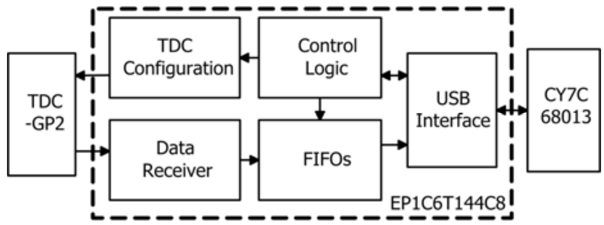

Fig.4 Block diagram of the FPGA logic.

Upon receiving a TDC control code from the control logic, the TDC configuration module generates a control data flow that is sent to the TDC to ensure the configuration is successful. The data receiver module receives TDC data by registering it in asynchronous first-in-first-out (FIFO) mode.

The USB interface module controls the transmission between FPGA and the USB interface chip CY7C68013. The CY7C68013 works in slave FIFO mode in which two buffers are used: EP2 and EP8. The EP2 is configured to be a data in (IN) endpoint of a triple buffering mode, which stores the data sent to the personal computer (PC) from the FPGA. The EP8 is configured to be a data out (OUT) endpoint, carrying the commands from the PC to the FPGA. In this application, bulk transfer and auto transmission mode are selected.

The control logic is the heart of the FPGA firmware, reading and interpreting the commands from the USB interface module. Depending on the given command, the control logic decides whether to pass the command onto the next module, or to execute the commands directly. Another important function of the control logic is to control the data transmission between the TDC and the FPGA.

4 Results and discussion

Specific tests were carried out to check the TMEB performance of the linearity,and resolution, and time walk of the CFD as well. These were done with an Agilent 33250A signal generator. The synch signal was used for a start and the output signal, delayed with an ORTEC DB463, was used as the stop[8]. The setup is shown in Fig.5.

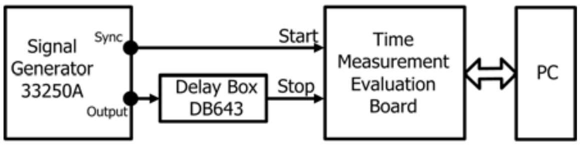

Fig.5 Block diagram of test setup.

4.1 Resolution

Time resolution of the TDC was measured. For reducing statistical error, each delay was measured one million times. Fig.6 shows the TDC counts histogram obtained for a fixed delay. By a Gaussian fitting to the counts distribution, the standard deviation σ is 0.54 channels, less than 1 channel. That means the time resolution is better than 61 ps.

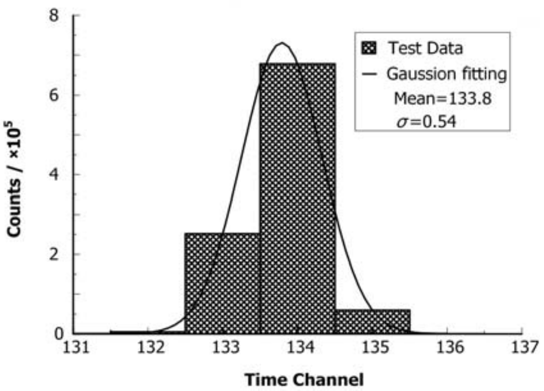

Fig.6 TDC counts histogram obtained with a fixed delay.

4.2 Linearity

The linearity was tested by varying the delay between the start and stop. By setting different delays we obtained the t_d-CH_G curve. The linearity and the converted slope of time measurement could be calculated using the t_d-CH_G curve. Fig.4 shows the mean value CH_G a function of the time delay t_d, which is measured by TDC-GP2, and the Gaussian fitting shows a good linearity.

When the TDC-GP2 is in the calibrated mode, the slope of t_d-CH_C line is the oretically 7.6 ps/channel. The TDC-GP2 uses internal propagation delays of signals through gates to measure time intervals with high resolution. The maximum possible resolution depends on the maximum possible gate propagation delay of the chip. The gate propagation cannot be achieved with such a high resolution, so channel binning should be done. Combining 8 channels result in 61 ps/channel. This is very close to the typical resolution (65 ps) of the TDC-GP2.

Figure 7 shows the mean value of the TDC channel, which obtained from a Gaussian fit to the measured data as previously discussed, for delays ranging from 0 to 550 ns. The slope of the line is found to be 60.8 ps/channel. The fitting results coincide with the theoretical value (61.0 ps). The correlation coefficient R of the line is 1, and the nonlinear error is lower than 0.15% of the full scale, thus the linearity is very good.

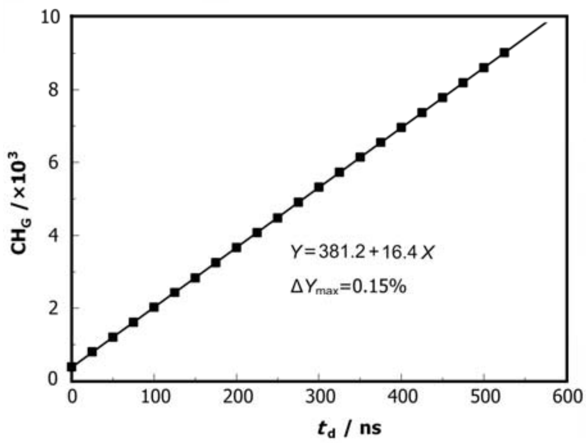

Fig.7 Linear fit of the data from different delays.

4.3 CFD test

For a fixed delay and a rise time of 5 ns, time interval was measured for signal amplitudes ranging from 50 to 500 mV. The mean value of each data point was obtained from a Gaussian fit. The results are shown in Fig.8. Over this range, the time walk of CFD is less than ±85 ps, and the RMS of time walk is about 55 ps. The results can prove that the design of the CFD circuit meets the requirement of the timing precision ($\sigma_C \approx$75ps).

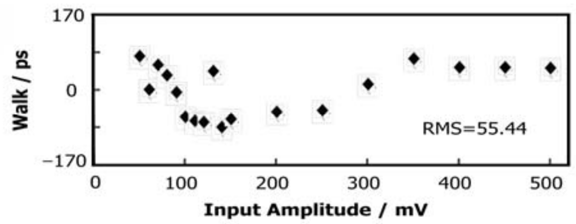

Fig.8 Timing walks *vs.* amplitude of input signal.

4.4 Cosmic-ray test

TMEB timing resolution in practice usage was evaluated by cosmic-ray measurement using a plastic scintillator detector, same as Fig.5, with the signal generator replaced with a plastic scintillator detector during about 21 hours. Fig.9 shows that one set of the data is along with a Gaussian fit. The standard deviation is 1.3 channels. This means that the overall time resolution of the TMEB is about 81 ps, which satisfying the radiography system requirement (σ_T≈100 ps).

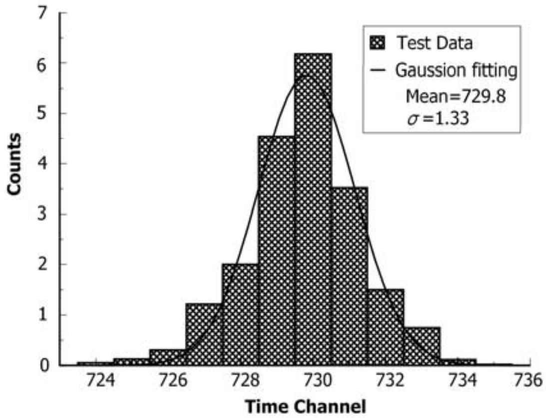

Fig.9 Time resolution using plastic scintillator detector.

5 Conclusion

In order to ensure the radiography system can achieve 1ns resolution, the electronics system time resolution must be less than 100 ps. The test result shows that the TDC-GP2's time resolution is about 61 ps, and the TMEB's time resolution is about 81 ps. The characterization results reported show that the TMEB hardware is fairly adequate for use with drift chamber in the radiography system. The drift chamber is still under development. Future work will include a combined test with the detector.

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