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Development of a data acquisition system for the $\mu$SR spectrometer prototype at the China Spallation Neutron Source

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ABSTRACT: An experimental muon source (EMuS) to provide a very intense muon beam has been studied at the China Spallation Neutron Source (CSNS) since 2007 and will be operational in the next few years. R&D efforts including a 128-channel muon spin rotation, relaxation, and resonance ($\mu$SR) spectrometer prototype are also ongoing. A data acquisition (DAQ) system was been developed to run the $\mu$SR spectrometer prototype on the EMuS. It includes front-end electronics (FEEs), time-to-digital converter (TDC) modules, and a DAQ software. The raw data acquired by the DAQ software were converted into a specific format and submitted to specialized analysis software for analysis. The DAQ system was tested on the ISIS muon beam, and the test results proved its performance.

KEYWORDS: Data acquisition circuits; Instrumentation and methods for time-of-flight (TOF) spectroscopy; Modular electronics; Muon spectrometers

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1 Introduction

The use of muon spin properties (normally $\mu^+$) to study the properties of materials is called the muon spin rotation, relaxation, and resonance ($\mu$SR) technique [1, 2]. The $\mu$SR technique is an important tool for studying materials. It can be used under extreme conditions where other nuclear detection techniques are not suitable, such as high temperature, high pressure, high magnetic field, light irradiation, etc., and is suitable for any form of material. The $\mu$SR technique has significant advantages, especially for the study of micro-magnetic properties. Currently, only four major muon facilities (ISIS [3], J-PARC [4], PSI [5], and TRIUMF [6]) have $\mu$SR spectrometers for $\mu$SR applications. An experimental muon source (EMuS) to provide a very intense muon beam has been studied at the China Spallation Neutron Source (CSNS) since 2007 [7–10]. R&D efforts including a 128-channel $\mu$SR spectrometer prototype are also ongoing. A data acquisition (DAQ) system was developed to run the $\mu$SR spectrometer prototype on the EMuS.

Currently, the $\mu$SR spectrometer prototype has 128 channels (64 front channels and 64 rear channels). It consists of a collimator, a monitor, external magnetic fields, a sample chamber, and 128 positron detectors. Figure 1 shows a schematic of the $\mu$SR spectrometer prototype being developed. A pulsed muon beam is generated by the CSNS proton beam hitting the muon target. The positron detectors detect the positrons generated by the decay that the muon injects into the sample ($\mu^+ \rightarrow e^+ + e^- + v_e + v_\mu$). A positron detector consists of a plastic scintillator, a light guide, and a photomultiplier tube (PMT). The DAQ system measures the time difference between the muon beam passing through the monitor (start) and the positron detector detecting the positron (stop). By analyzing the time spectrum, the microscopic information of the sample can be determined.
Figure 1. Schematic of the $\mu$SR spectrometer prototype.

2 DAQ system

There are three key parameters for the time measurement of the $\mu$SR spectrometer: dead time, depth of hit buffer, and time precision. When each pulsed muon bunch of about width 50 ns is injected into the sample, many positrons are produced. These positrons are all expected to be recorded, so theoretically the dead time is as small as possible. A large depth of hit buffer is also necessary to store these hit events. The $\mu$SR spectrum is a spectrum of counts versus time, and the time is divided into many nanosecond intervals. Good time precision can make the time distribution more accurate. If any of the three parameters is insufficient, the time spectrum will be distorted. In addition, it is necessary to have enough data transmission speed to upload data from all of the channels to the PC.

We investigated the $\mu$SR spectrometers of four muon facilities (ISIS, J-PARC, PSI and TRIUMF). Among them, J-PARC’s $\mu$SR spectrometer was the most recently built. Its PMT-based DAQ system constructed in 2009 has a timeresolution of 1 ns and a hit buffer depth of 1024 per channel. The data transmission speed is 100 Mbps. But the dead time is not mentioned [11]. In theory, high-intensity pulsed muon beams can increase the count rate. However, the count rate is limited by the detector. The typical recovery time of PMT is approximately 20 ns and the typical recovery time of a silicon photomultiplier (SiPM) is approximately 40 ns. Thus, the count rate of a single-channel detector cannot be greatly increased. Even if it is considered that the positrons arrive uniformly within 2.2 $\mu$s and the dead time is 20 ns, the count rate of a single channel is only 2.2 us/20 ns =110 counts/pulse. But most of the positrons are generated in the early stage of muon decay, so the actual count rate will be lower. The usual way to increase the count rate is to increase the number of detectors. In 2014, J-PARC developed a new 1280-channel $\mu$SR spectrometer based on SiPM [12]. Compared to other pulsed muon sources, the EMuS has a lower count rate per second because it has a repetition rate of only 2.5 Hz. Although this $\mu$SR spectrometer prototype currently has only 128 channels, it will definitely be upgraded to more channels in the future. In addition, other $\mu$SR spectrometers, especially SiPM-based super-$\mu$SR spectrometers, are also planned [10].

Considering the previously mentioned characteristics of the $\mu$SR spectrometer, a PMT-based DAQ system has been developed. Its dead time is less than 20 ns and the hit buffer depth is up to 512 per channel (this depth is completely sufficient). The time resolution is 312.5 ps. Gigabit
Ethernet data transmission is implemented in a field programmable gate array (FPGA) to be able to cope with even more channels in the future. It consists of three parts: front-end electronics (FEE), a time-to-digital converter (TDC) module, and DAQ software. Both the FEE and TDC module are designed to be the size of a 6 U NIM plugin. Figure 2 shows a schematic of the DAQ system. The signals from 128 channel positron detectors are connected to 16 FEEs via long coaxial cables. The FEE converts the detector signals into timing pulses and passes them to the TDC module for time measurement. Each FEE has 8 electronics channels. Four FEEs are connected to one TDC module. One TDC module has 32 electronics channels and is responsible for time measurement and high-speed data transmission. The measurement results are uploaded to the DAQ software. The start signal comes from a common start provided by the EMuS and fans out to the four TDC modules.

![Figure 2. Schematic of the DAQ system. FEE: front-end electronics; TDC: time-to-digital converter; DAQ: data acquisition.](image)

### 2.1 FEE design

The timing precision directly affects the time precision of the entire DAQ system. The conventional delay line constant fraction discriminator (CFD) circuit is bulky. To improve the integration and ensure high timing precision, a CFD with non-delay-line circuit is adopted. Timing precision of 55 ps and the time offset versus amplitude of 255 ps are achieved [13].

Each FEE has 8 electronic channels connected to the output of 8 PMT channels, as shown in figure 3. The negative pulse signals from the PMTs are converted into timing pulses by the CFD circuits. The 8 timing pulse signals are converted into low-voltage differential signal (LVDS) level signals and then routed to a 34-pin connector. An Altera cyclone FPGA receives commands from the TDC module to control a 2-channel 12-bit digital-to-analog converter (DAC), an 8-channel 8-bit DAC, and 8 analog switches and sends status information to the TDC module. The 12-bit DAC is responsible for controlling the amplitude of the self-test pulse and the bias of the 8 CFDs. The 8-bit DAC is responsible for controlling the discriminator thresholds of the 8 CFDs. The 8 discriminator...
thresholds can be set uniformly or separately. The 8 analog switches are responsible for providing periodic self-test pulses to simulate the signals from the detectors.

**Figure 3.** Schematic of the FEE board.

In the µSR experiment, on the one hand, it is desirable to detect more events. On the other hand, the background noise must be suppressed as much as possible. Thus, it is very important to have an accurate threshold setting. The CFD threshold setting circuit is shown in figure 4. The reference level of the 8-bit DAC (DAC088S085) is 0.5 V and the two resistances maintain the relationship of $R_1 = 2 \times R_2$. Thus, the resolution of the threshold is $3 \times 0.5/2/2^8 \approx 3 \text{ mV}$ ($V_{th} = (3 \times V_{out} - 0.5)/2$).

**Figure 4.** CFD threshold setting circuit.

### 2.2 TDC module design

The design of the TDC module is the key to the entire DAQ system because it must meet the requirements of dead time, depth of hit buffer, time precision, and high-speed data transmission at
the same time. Some commercial TDC chips may meet some of these requirements, but few TDC chips can have a very large depth of hit buffer (more than 110). Because the FPGA is very flexible and its performance is growing more powerful, it is often used for design, including TDC design. In the TDC module, 32-channel TDC, Gigabit Ethernet data transmission and communication with the FEEs are implemented in a single FPGA [14].

Figure 5 shows a schematic of a TDC module board. The core device is a Xilinx Virtex-6 FPGA. There are two double-layer 68-pin connectors on each TDC module. Four FEEs are connected to a TDC module via four 34-pin flat cables. The 32 timing signals from the four FEEs are connected to the FPGA through the LVDS buffer. The TDC module communicates with the FEEs via the serial peripheral interface (SPI) protocol. The start and trigger signals are connected to the TDC board via the LEMO connector and passed through a high-speed comparator to the FPGA. The start and trigger inputs can be various logic levels such as NIM, CMOS, TTL, ECL, and LVDS. The 32-channel TDC is implemented in the FPGA. The input signal is sampled by 16 phase-shifted 200 MHz clocks to achieve a resolution of 312.5 ps. The depth of the hit buffer is currently set to 512 per channel and can be flexibly adjusted if necessary. The dead time is less than 10 ns. Each time measurement data is channel-encoded and then packed into 64-bit data (including 7-bit channel coding, 20-bit time measurement, 8-bit trigger count, 26-bit time tag, and 3-bit unused bits) and stored in the first input first output (FIFO) readout. The 20-bit time measurement records the time difference between the Start signal and the Stop signal. The 26-bit time tag is used to record the arrival time of each event. It is provided by a 26-bit counter driven by a 25 MHz low-speed clock with a measurement range exceeding the interval of two pulses of muon beams (2.5 Hz repetition rate). This tag provides a global time reference for each event to construct a dataset. The data are finally uploaded to the DAQ software via the Gigabit Ethernet. Gigabit Ethernet communication is based on a Gigabit Ethernet IP core working at the media access control (MAC) layer in the FPGA and an external Gigabit Ethernet transceiver working at the physical layer. USB 2.0 is used as an alternative. The DAQ software can also configure the TDC module (including shielding data from certain channels or setting time window) and communicates with the FEEs (including receiving status information, controlling the DACs, and controlling the analog switches) via the Gigabit Ethernet.

Due to printed circuit board (PCB) traces and the internal routing of the FPGA, there is always a certain difference in the delay of each channel. This means that the time precision of the entire electronics is degraded because the data for all of the channels are ultimately analyzed together. Thus, a self-test circuit was designed to calibrate it.

The time sequence of the self-test circuit is shown in figure 6. The TDC module provides a 25 MHz communication clock. When the DAQ software issues a self-test command, the TDC module periodically generates two pulse signals (TDC_TEST_START and TDC_TEST_STOP). TDC_TEST_STOP controls each analog switch on the FEE to generate a signal (SELF_TEST_PULSE) similar to the detector’s output. The CFD circuit converts this signal into a timing pulse (CFD_TIMING_PULSE) that is then received by the FPGA on the TDC module. By measuring these time differences, the delay difference between the different channels is elucidated. It also can determine if the entire DAQ system is working properly.
Figure 5. Schematic of the TDC module board. LVDS: low-voltage differential signal; FIFO: first input first output; SPI: serial peripheral interface.

Figure 6. Time sequence of the self-test circuit. The TDC module generates a start pulse and controls the analog switch to generate the FEE input signal. The TDC module measures the time difference.

2.3 Software structure

The DAQ software is mainly responsible for data acquisition, command delivery, and data format conversion. The DAQ software is written in C++ language based on the Microsoft Foundation Classes (MFC) framework of the Visual Studio development kit. Windows packet capture (WinPcap) is used to implement network communication in the form of underlying capture. Each TDC module is assigned a different MAC address and WinPcap identifies them based on the MAC address.

2.3.1 DAQ software

A block diagram of the DAQ software (in addition to the data format conversion) is shown in figure 7. Initialization involves selecting a network card, configuring WinPcap, and filtering MAC
addresses. A normal working mode (data acquisition) and test mode (self-test) can be selected. The parameters that need to be set include the time window, channel shielding, discriminator thresholds, CFD bias, file size, number of files, and storage location. There are two modes of data upload. One is “always upload.” After setting the size of a file package, the data will be uploaded until the user manually stops. The other is “conditional upload.” After storing a fixed size and number of files, the program will stop automatically. The files include data files and record files. The data file stores the raw muon data. The record file records the start time, stop time, and timeout time. If no data are obtained for a long time, a notification will appear on the display panel.

**Figure 7.** Block diagram of the DAQ software (in addition to the data format conversion). After initialization, the corresponding parameters are set and then the data are uploaded.

### 2.3.2 Data format conversion

It is very important to analyze the data efficiently and conveniently. MANTID [15] provides a means of analyzing muon data from many facilities’ instruments. NeXus [16] is a universal data exchange format for neutron, X-ray, and muon experiments and is supported by MANTID. NeXus is built on top of the scientific data format HDF5 [17] and adds domain-specific rules. Thus, a data format conversion program is designed in the DAQ software based on the HDF5 library functions. The raw muon data and other key features such as the sample conditions, instrument information, user information, and log files are converted into the NeXus file for analysis as shown in figure 8. Furthermore, it provides the possibility to share muon data and communicate with other muon facilities.
3 Test results

3.1 Electronics test

When the DAQ system is working under muon beam conditions, it is necessary to find the best amplitude point between the background noise and the events by measuring its amplitude spectrum. But there is always a difference between the theoretical threshold issued by the DAQ software and the signal amplitude that can be distinguished. The relationship between the threshold and the amplitude of the input signal was tested three times. The test results are shown in figure 9. The correlation coefficient $R^2$ is 0.9986.

![Figure 9](image)

**Figure 9.** Fitting curve of the threshold versus the input signal. The correlation coefficient $R^2$ is 0.9986.

A Tektronix AFG3252C dual-channel arbitrary/function generator was used to measure the DAQ system’s precision and linearity. The signal frequency is controlled to non-correlate with the frequency of the TDC’s 200 MHz sampling clock and the time interval is incremented from 10 ns to 265 ns every 5.1 ns. A total of three tests were performed. A measured time precision is shown in figure 10. The full width at half maximum (FWHM) precision is 0.408 ns (calculated by
FWHM = 2.355×RMS). The curve of the FWHM precision versus input time interval is shown in figure 11, the worst is 0.425 ns (including the time precision of the AFG3252C, the RMS precision is typically 35 ps). The fitting curve of the expectation versus the input time interval is shown in figure 12. The correlation coefficient R^2 is 0.99999998.

Figure 10. A FWHM precision measured with the signal generator. The FWHM precision is 0.408 ns.

Figure 11. The FWHM precision vs. input time interval. The worst FWHM precision is 0.425 ns.

To measure the dead time, one channel of the Tektronix AFG3252C dual-channel arbitrary/function generator is used to generate a pulse signal with a frequency of 1 kHz (start). The other channel generates 10 consecutive pulse signals that are triggered by each start signal (stop).
The width and interval of these 10 pulses are both 10 ns. The spectrum of the counts versus the time in MANTID is shown in figure 13. There are 10 groups of counts and the count values are equal, equal to the start count. A total of three tests were performed and the test results were consistent. It also tested a start corresponding to more stops (such as 30, 50, and 100). The test results show that the count values are still equal. Therefore, the dead time of the entire DAQ system is less than 20 ns.

Figure 13. Spectrum of the counts versus the time in MANTID. There are 10 groups of counts and the count values are equal.

3.2 Performance test of connecting PMT

The time precision and dead time of the DAQ system connected to the Hamamatsu R6427 PMT (used by our μSR spectrometer prototype) have also been tested. The test scheme was designed as shown in figure 14. The pulse signal from one channel of the signal generator is directly connected
to the TDC module (start). The R6427 was placed in a dark box, and the pulse signal from the other channel drives the LED to illuminate. The output of the R6427 (stop) is connected to the FEE. A total of three tests were performed, and the worst FWHM precision is 0.676 ns as shown in figure 15.

Figure 14. The test scheme of the time precision and dead time. The signal generator drives the LED to illuminate. The output of the R6427 is connected to the FEE.

One channel of the signal generator outputs a pulse signal with a frequency of 1 kHz (start), and the other channel outputs 10 consecutive pulse signals that are triggered by start signal to drive the LED to illuminate (stop). Change the interval between stops (by changing the frequency of the stop signal), and then measure the count rate ratio. A total of three tests were performed and the count rate ratios at different stop pulse frequencies between using this test scheme and directly using the signal generator were compared as shown in figure 16. When using this test scheme, the count rate ratio starts to decrease at the frequency of 40 MHz, and it drops directly to approximately 14% at the frequency of 45 MHz. When using the signal generator, the count rate ratio is stable at 100% until 60 MHz. The RC network in the CFD circuit of the FEE [13] will slow the trailing edge of the input signal, while the signal generator’s signal has a faster trailing edge, which is less affected. However, the trailing edge of the PMT’s signal is close to 20 ns. Although it has no obvious pileup at 45 MHz, the RC network causes it to pile up in advance in the CFD circuit. Eventually the dead
time of connecting the PMT increases to approximately 25 ns. Subsequent we consider adding a zero-pole cancellation circuit in front of the CFD circuit to make the trailing edge of the PMT faster, thus reducing the dead time.

![Figure 16. Comparison of the count rate ratio at different frequencies (the signal generator vs. the R6427). When using the R6427, the count rate ratio drops to approximately 14% at the frequency of 45 MHz. When using the signal generator, the count rate ratio is stable at 100% until 60 MHz.](image)

3.3 Muon beam test

The DAQ system was tested on EMU [18–20] (a new 96-detector µSR spectrometer based on a PMT) in ISIS, U.K., in September 2018, mainly to test two key parameters: the experimental dead time and the observable muon decay asymmetry. The experimental dead time calculation is through the standard algorithm “CalMuonDeadTime” in MANTID. The experimental dead time of our DAQ system (Chinese DAE) and the ISIS data acquisition electronics (ISIS DAE) under different muon beam slits is shown in figure 17. Silver was used as a standard sample under zero field conditions. The bin size is set to 16 ns. Different slit widths correspond to different beam intensities. The larger the slit, the higher the beam density, and the more the number of positrons received by each detector. The test results show that as the slit width increases, the experimental dead time increases, but within a reasonable range.

We also give a comparison of the mean count rate per muon pulse as shown in figure 18. It can be seen that compared to ISIS DAE, the mean count rate of Chinese DAE is higher and there is a non-linear situation, which is due to the lower threshold in Chinese DAE. The threshold of ISIS DAE is -75 mV, and our threshold is set to the corresponding threshold when the input signal is -75 mV, so in fact our threshold is closer to the background noise’s amplitude. When the slit width is relatively low, the count rate is low and the counting loss is also low, so the dead time is relatively small. As can be seen from figure 17, when the slit width is less than 20 mm, the dead time of ISIS DAE and Chinese DAE are both smaller. Due to the lower threshold, Chinese DAE detects more noise, but the noise is evenly distributed in time, more noise will not affect the dead time of the
Figure 17. The experimental dead time of the Chinese DAE and the ISIS DAE under different slits (analyzed by MANTID). As the slit width increases, the experimental dead time increases.

Chinese DAE; when the slit width increases, the counting loss increased and the dead time of both ISIS DAE and Chinese DAE increased. The lower threshold brings more noise and higher count rate, and the counting loss is more obvious, so the Chinese DAE has a significant inflection point under the 50mm slit. Although the noise itself does not affect the dead time, it reduces the number of valid events, so the death time of the Chinese DAE is significantly increased in the 50mm slit.

Figure 18. The mean count rate per muon pulse of the Chinese DAE and the ISIS DAE under different slits. As the slit width increases, the mean count rate increases.

To measure the asymmetry, silver was used as a standard sample under a 100 Gauss magnetic field. Chinese DAE and ISIS DAE are connected to different PMTs on the same detector ring.
of the EMU. The asymmetry is analyzed by the Origin (fitting function $y = A1 \times e^{-t/2.197} \times (1 + A2 \times \cos(A3 \times t + A4)) + A5$, and then removing its exponential component from the original data). The analysis results are shown in figure 19. The asymmetry measured by the Chinese DAE is equal to the asymmetry measured by the ISIS DAE. The asymmetry measured by the Chinese DAE may have more noise, because Chinese DAE has a lower threshold setting and the total count of statistics is only half of the ISIS DAE.

![Figure 19](image)

**Figure 19.** (a) Asymmetry of the Chinese DAE. (b) Asymmetry of the ISIS DAE (analyzed by the Origin). The asymmetry measured by the Chinese DAE is equal to the asymmetry measured by the ISIS DAE.

### 4 Conclusion

To run the 128-channel μSR spectrometer prototype on the EMuS at CSNS, a DAQ system was developed. The system is specifically designed for a low dead time, an instantaneous high count rate, and high-precision requirements in the μSR experiments and completes high-speed data transfer and specific data format conversions. The entire system can be diagnosed without the detectors’ connection. The performance was tested in detail and a successful muon beam was conducted on the EMU at ISIS. The overall performance of the system meets the design requirements, even if the μSR spectrometer is upgraded to more channels in the future.

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References


