Technical Report

The electronics and data acquisition system for the PandaX-I dark matter experiment

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Abstract: We describe the electronics and data acquisition system used in the first phase of the PandaX experiment — a 120 kg dual-phase liquid xenon dark matter direct detection experiment in the China Jin-Ping Underground Laboratory. This system utilized 180 channels of commercial flash ADC waveform digitizers. During the entire experimental run, the system has achieved low trigger threshold (<1 keV electron-equivalent energy) and low deadtime data acquisition.

Keywords: Front-end electronics for detector readout; Modular electronics; Control and monitor systems online

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1 Introduction

The PandaX project consists of a series of experiments at the China Jin-Ping Underground Laboratory, utilizing xenon-based time projection chambers (TPC). The first phase experiment, PandaX-I [1–3], with a 120-kg dual-phase xenon dark matter detector, completed its data taking in October 2014. The TPC of PandaX-I had a cylindrical shape with 60 cm diameter and 15 cm height, confined by the cathode plane located at the bottom in the liquid xenon, and a gate and anode planes located 4 mm below and above the liquid level, respectively. Particle interactions in the xenon produce prompt scintillation photons (S1). Some of the electrons from ionization produced in the same interaction drift vertically upward between the cathode and gate, and get extracted by a stronger field between the gate and the anode into the gas, producing proportional scintillation photons (S2). The background gammas produce electron recoil events, while the dark matter signals interact with xenon atomic nucleus producing nuclear recoil events. The ratio of S2 to S1 is less for the latter compared to the former due to different ionization capability. This ratio is therefore used as an effective background discrimination parameter. Two arrays of photomultiplier tubes (PMTs) consisting of 143 1-inch R8520-406 tubes and 37 3-inch R11410-MOD tubes from Hamamatsu [4]
were located at the top and bottom, respectively, looking into the TPC collecting S1s and S2s. The time difference between S1 and S2 signals gives the vertical position of the interaction, and the charge pattern of S2 signals on the PMT arrays encodes the horizontal position.

Being an underground experiment for very rare event search, the design philosophy of the electronics and data acquisition (DAQ) system of PandaX-I was to maximize the data collection under the lowest possible threshold, and leave the “data mining” work to the offline analysis. The system digitizes the waveforms from the PMTs, generates triggers on candidate signals, and saves the data to disks. The remainder of this paper is organized as follows. In section 2, the requirements of the system are presented, followed by the design details of the electronics in section 3 and DAQ in section 4. We summarize the performance of the system during the experiment in section 5 before the conclusion.

2 System requirements

The typical dark matter recoil signals deposit small amounts of energy from sub-keV to a few tens of keV. For PandaX-I, this translates into a typical S1 from 1 to 100 photoelectrons (PE) with a time range of 100 ns, combining all PMTs. The intensity of the corresponding S2 signal is typically one hundred times that of S1 (100 to 10000 PE) with a time span of \( \sim 2 \mu s \) determined by the properties of the gas and the gap between the gate and anode. There are two general requirements for the PandaX-I electronics.

- To achieve a low energy threshold of \(< 1 \text{ keV}_{\text{ee}}\) electron equivalent energy (relating to the true nuclear recoil energy by the so-called Lindhard factor).
- To digitize and read out the waveform faithfully from each PMTs for offline analysis.

| Trigger threshold | $< 1 \text{ keV}_{\text{ee}}$ |
|-------------------|-----------------|
| S1 signal         | [1, 100] PE in 100 ns |
| S2 signal         | [100, 10000] PE in 2 \( \mu s \) |
| Readout window    | 100 \( \mu s \) pre- and post-trigger width |
| Digitizer ADC resolution | 14 bit, 2 V range |
| Digitizer sampling rate | 100 MS/s |
| Maximum rate      | 30 Hz (source calibration), 10 Hz (dark matter), 100 Hz (LED) |
| Number of channels| 180 |
| Maximum data bandwidth | 70 MB/s with baseline suppression |

These two general requirements are shown more specifically in table 1. For PandaX-I, the maximum electron drift length is 15 cm, corresponding to an 88 \( \mu s \) maximum separation between the S1 and S2 with a drift speed of \( \sim 1.7 \text{ mm/}\mu s \). To allow the trigger to be generated either by S1 or S2, the readout window should have an equal pre- and post-trigger width of at least 88 \( \mu s \). To be
able to cleanly monitor random light generation in the detector, the readout window was selected to be ±100 µs before and after the trigger. The single photoelectron (SPE) signals, assuming an overall gain of $2 \times 10^7$, are about 10 mV in amplitude with a full-width-half-maximum of about 20 ns and a full range of about 100 ns (see later figure 5), resulting in an approximate 10 mV×20 ns conversion factor from pulse area to a SPE. According to a simulation including digitization and bandwidth effects, in order to achieve a <5% bias to the charge of a single photoelectron, a 100 MS/s sampling rate and a 14 bit ADC (with full range ~2 V) is required.

The requirement on data bandwidth depends on the types of data runs in PandaX-I. The first type is the low occupancy LED run to calibrate the gains of the PMTs, in which the fast light pulses from external LEDs were injected into the detector with the system triggered by the LED driving pulses (~ 100 Hz). Such a type of run can have a short readout window (~ 1 µs) and therefore has a small event size. The second type is the calibration run with gammas and neutrons, which is required to achieve a rate of ~30 Hz in order to collect sufficient calibration data within a few days. The third type is the normal dark matter search run, in which the trigger rate is expected to be <10 Hz based on the Monte Carlo simulation. Clearly the latter two types are required to have a long readout window of ~200 µs, and the source calibration runs dictate the data bandwidth requirement. Taking the 14 bit ADC and 100 MS/s sampling rate, the estimated bandwidth is 210 MB/s if no data reduction is used on the digitizer data. In reality, the baseline data can be suppressed (see section 3.2.2), leading to at least a factor 3 reduction in data rate (70 MB/s).

3 System design

3.1 Electronics system

A schematic diagram of the electronics and DAQ system is shown in figure 1. The system is very similar to the one used in the XENON100 experiment [5]. The high voltage (HV) mainframe SY1527LC with four A1932AP 48-channel positive HV modules were used as the HV supplies for the PMTs in both arrays. The raw signals from the PMTs were transmitted out of the detector together with the HV on the same coaxial cable and were separated via a capacitive decoupler outside the detector [1]. Since the average gain of the PMTs was $2 \times 10^6$, to achieve a $2 \times 10^7$ gain as mentioned in section 2, the raw PMT signals were amplified linearly by a factor of 10 by the Phillips 779 amplifiers before entering into the CAEN V1724 (8 channels per VME module) digitizers [6]. The V1274 digitizer stored data in buffers which were read out upon receiving the trigger signal generated by the trigger system. The scaler unit (CAEN V830) counted both raw and system trigger signals to monitor the system deadtime.

3.2 Digitizers

The central components of the electronics are 23 VME modules of CAEN V1724 digitizers, located in two VME crates, connected through optical fibers. Each V1724 supplies eight channels of 14-bit 100 MS/s flash ADC (FADC) with 2.25 V$_{pp}$ dynamic range, leading to 0.137 mV for the least significant bit. Each of the 180 PMT signals is connected to a FADC channel. Taking the approximate 10 mV × 20 ns/SPE conversion factor mentioned in section 2, the maximum S1 (~100 PE, 100 ns) and S2 signals (~10000 PE, 2 µs) in the dark matter search region will have an
amplitude of 400 mV and 2 V, respectively, assuming a triangular shape of the waveform, even if all photons are collected by a single PMT.

Each V1724 has an independent 100 MHz internal clock. It allows synchronization among boards by using the CLK-OUT from a given board as the master, and daisy-chaining the CLK-IN and CLK-OUT of the rest of the boards with a programmable phase for each CLK-OUT signal. All 23 VME boards were verified to be synchronized to better than 2 ns by routing the CLK-OUT from each board into the oscilloscope. This is sufficiently precise for this experiment given that a typical S1 signal is roughly 100 ns wide.

### 3.2.1 Majority signal

Each V1724 board houses a 12-bit 100 MHz DAC with 1 V range on a 50 Ohm load and the output is available on the “MON/∑” connector on the front panel. Each FADC channel generates a time-over-threshold signal on a preset threshold (high = 125 mV), and the internal sum of eight channels is output by the DAC. The area of this so-called MAJ signal encodes the overall PE values in this
board for small signals when PEs are not piling up in the waveform. In PandaX-I, the threshold for the majority signal was set to be \( \sim 1 \) PE for each channel. The MAJ signals are used in the trigger generation, which will be discussed in detail in section 3.3.

### 3.2.2 Zero suppression

The CAEN V1724 has the capability to record the waveforms in a Zero Length Encoding (ZLE) mode, discarding the data under a threshold set by the user. In PandaX-I, after the gain stage, we chose the amplitude of 1/3 PE as the threshold for the waveform suppression. The efficiency for such a threshold was studied by comparing the low intensity LED run with and without the ZLE to be nearly 100%. To allow proper baseline determination, we set the “look back” and “look forward” samples before and after the threshold crossings both to 40. In PandaX physics runs, ZLE mode compresses the data by a factor of 7. Even with the 30 Hz source calibration data, the achieved data rate is 30 MB/s, far less compared to the 70 MB/s data acquisition bandwidth (see section 5.2).

### 3.3 Trigger system

The general requirement for the trigger system is to achieve a low energy threshold \(< 1 \text{ keV}_{ee}\). To accomplish this, the actual design has to take into account two important issues. First, since signals from many PMTs are involved in generating the trigger, the trigger needs to be robust against coherent noise among channels. In PandaX-I experiment, we observed coherent short and fast oscillating pulses (\(\sim 100\) ns) from electromagnetic pickups occurring at a frequency of 200 kHz, that originated from the CAEN SY1527LC power supply. Under these circumstances, neither number-of-hit nor summed-signal-amplitude work well as a trigger source. Second, for the few-PE level S1 signals, it is very difficult to discriminate against noise in the trigger hardware. In this case, triggers on S2 signals (typically one hundred times larger) are much more effective. However, for small S2 signals, each PMT receives a few PEs but distributed broadly in a few \(\mu\text{s}\), a challenge for the trigger system to identify.

In figure 2, an illustration of the PandaX-I trigger generation is shown. In the PandaX-I detector, both S1 and S2 light collections are dominated by the bottom 3-inch PMTs, read out by five V1724 modules, each with its own 100 MHz MAJ output (section 3.2.1). As shown in figure 1, a Phillips 740 linear Fan-in/out module sums up the MAJ outputs from the five modules producing an analogue signal S0, which is a global time-over-threshold signal with its amplitude representing the number of fired bottom PMTs. S0 is then integrated by an ORTEC 575A spectroscopy amplifier (gain 25, shaping time 1\(\mu\text{s}\)) with the amplitude of the output proportional to the area of S0. The integrated signal is further discriminated by a CAEN V814 VME discriminator to generate the raw trigger signal. Such a trigger scheme is effective to address the two issues above. The short coherent noise, even if it happened to cross the majority threshold on a number of channels, would only produce a narrow S0 signal, whose integral would be too small to trigger. Small and narrow S1 would not generate the trigger either. On the other hand, for the broad and low amplitude S2 signals, the integral of S0 approximately represents the overall charge. The discriminator threshold is set to 15 mV, which is sufficiently low to trigger \(< 1 \text{ keV}_{ee}\) events efficiently (see section 5.1).

\footnote{Note that the noise ripple specification for CAEN SY1527LC is 30 mV\text{pp}, and what we observed was within this specification.}
Figure 2. a) the 100 MHz clock signal, b) and c) the waveforms of two FADC channels with dashed line indicating the majority threshold where the over-threshold samples produce majority output in the unit of 125 mV per channel, d) the summed majority signal S0, e) the integrated S0 signal after the spectroscopy amplifier, and f) the digital signal of the raw trigger.

V1724 uses a circular buffer to store data in its 1 MB memory to mitigate the deadtime during data readout. BUSY signals are generated when the buffer is “almost full”. The raw trigger signal and BUSY signals of the 23 V1724 are input into a CAEN V1495 general logic unit. To avoid multiple trigger signals within the length of a readout window (200 µs), a hold off window of 200 µs is set after a raw trigger. The system trigger is generated by the FPGA in V1495 that requires a raw trigger not being vetoed by any of the BUSY signals.

4 DAQ system

4.1 Architecture

The DAQ system reads out and processes the data from the electronics via the VME controller and optical bridges. As shown in figure 3, the DAQ server communicates with the VME electronics through optical fibers with a PCI-e interface card (CAEN A3818C), capable of hosting up to 4
optical fiber links. The DAQ uses one optical link to control the VME bus through the controller module CAEN V2718. The DAQ reads out the data from V1724 directly via three optical links, each connecting up to 8 daisy-chained V1724.

![Diagram of DAQ system architecture](image)

**Figure 3.** Hardware and software architecture of the DAQ system.

### 4.2 DAQ software

The DAQ software was developed in house in C++, with external libraries from CAEN (figure 3), as well as the XML and MySQL libraries. At the beginning of a run, the system resets all VME modules and clears buffers. All modules are initialized with configuration parameters specified in a user XML file. After the successful initialization, the system accepts the “run start” logic, and writes corresponding run configuration information into a MySQL database. MBLT (multi block transfer) mode is used to read out every five events stored in the V1724 circular buffer.

The DAQ contains an event builder to construct the event, consisting of the header such as DAQ status, configuration, event status, as well as the FADC data blocks. The FADC data blocks contain auxiliary information about the VME crate, board number, channel number, and time stamps, etc., to facilitate the offline analysis. A long run is broken into number of files, each with a size limit of 1 GB. At the opening and closing of each data file, the DAQ also inserts corresponding information into the MySQL database.

An issue was identified in which the data from different V1724s could occasionally get misaligned, making it nearly impossible to reconstruct the original events. The issue was due to the loss
of synchronization between clocks on different V1724s. To combat this, the DAQ system used the V1495 module to send out a trigger time reset signal at the “RUN START”. In addition, a method was implemented in the DAQ software to check for a difference in the timestamps between the first and last V1724 data block within an event, and forced the run to stop if a problem was found. These implementations fixed the problem.

In the stable running period, to achieve a complete automation of the DAQ, a background watchdog program restarted the run if there was a crash.

4.3 Realtime and online data processing and monitoring

The online data processing and quality monitoring scheme is shown in figure 4. The DAQ server was located underground in the electronics rack with disk arrays attached to it. To achieve real time monitoring of the DAQ performance, a process on the DAQ server parsed the output file as the data were being written onto the disk, producing low-level data-quality plots such as the trigger rate, PMT hit maps and waveforms, etc., viewable from a web page. As soon as a file was closed, a file copier program on the DAQ server would copy it to a network attached storage server located outside the laboratory, connected to the underground lab through fiber links. The storage server was attached to a multi-core processing server. Once the copying of a new file was completed, an analysis program would be triggered, generating output root files available for online analysis. Data quality figures of the run, up to the most recent file, would also be automatically generated, viewable on the web page.

During the smooth running period, the maximum data copying rate was tested to be 60 MB/s, corresponding roughly to a trigger rate of 85 Hz with a 200\(\mu\)s readout windows on all channels and the baseline suppression enabled.\(^2\)

\[^2\]Note that the data copying speed depends on the network connection, which should not be confused with data taking bandwidth between the digitizer and the DAQ server.
5 System performance

The electronics and DAQ system functioned stably during the PandaX-I data taking. Detailed analysis for the final dark matter exposure has been published [3]. Here we restrict the discussions to the performance of the system.

5.1 Electronics performance

The central components of the electronics system are the waveform digitizers. A typical waveform from a 3-inch PMT in a given event is shown in figure 5, in which a clear S1 and S2 signal is observed. The flat regions on the waveform correspond to the baseline which is suppressed by the ZLE. For each unsuppressed waveform segment, sufficient pre- and post-threshold-crossing samples were saved, based on which the baseline noise could be computed. On average, the baseline noise was $\pm 0.7$ mV, in comparison to the average amplitude of the SPE which was 10 mV. The noise level obtained during the LED calibration run with ZLE disabled was consistent.

![Waveform](image)

**Figure 5.** A typical PMT waveform from a nuclear recoil event with a single S1 and S2. An enlarged view of the S1(S2) waveform is also shown.

The most important performance parameter is the trigger threshold. As mentioned in section 3.3, the trigger was generated from the S2 signals for the low energy events in the dark matter search region, and the corresponding S1s were identified by offline software. In figure 6a, the charge of S1 vs. the leading edge time of S1 is shown. The bright vertical band around 100 $\mu$s...
corresponds to the events triggered by S1 with a charge larger than $\sim 65$ PE. The preceding lower band corresponds to the S2 triggered events with lower values of S1. The events with S1 $> 100$ $\mu$s are from the afterpulsing of PMTs after large S2 signals but identified as S1s. To study the threshold for S2, the low energy nuclear recoil events in the $^{252}$Cf calibration data were taken with their S2 distribution shown in figure 6b. For these events, the true S2 distribution is expected to approximately be an exponential shape according to the Monte Carlo. The measured S2 distribution was then fitted in which the trigger efficiency function was modeled as a Fermi-Dirac function. The resulting threshold was $89.0 \pm 1.6$ PE for a 50% efficiency. According to the energy model used in ref. [3], the mean value of (S1, S2) for a 1 keV$_{ee}$ electron recoil (background) and nuclear recoil (signal) events are (1.6, 867) PE and (3.7, 525) PE, respectively. Clearly the trigger performance satisfies the threshold requirement in table 1.

5.2 DAQ performance

The limitation of the DAQ data rate was measured with the LED calibration runs without zero suppression by increasing either the rate of the LED forced triggers, or the length of the readout window. The results are shown in figure 7. One sees that in both measurements, the DAQ rate saturated consistently at around 70 MB/s. Shown in table 2 are the typical data rates of the four different run modes in PandaX-I, all significantly less than the 70 MB/s measured upper limit of the bandwidth. One expects nearly deadtime-less operation under such rates.

6 Summary and conclusions

We have described the electronics and data acquisition system for the PandaX-I dark matter direct detection experiment. This system used commercial electronics modules but custom-developed trigger system and DAQ software. The system ran steadily for more than nine months and collected
Figure 7. Studies on the data readout limitation using the LED forced triggers by varying the forced trigger rate (left) and event size (right). In both figures, red triangles and open circles represent DAQ live ratio (scale on the left) and data transfer rate (scale on the right), respectively.

Table 2. Basic DAQ parameters and data rate for different run modes in PandaX-I.

| Run mode | \(^{60}\)Co | \(^{252}\)Cf | LED | DM |
|----------|-------------|-------------|-----|----|
| Readout window(µs) | 200 | 200 | 5.12 | 200 |
| ZLE | YES | YES | NO | YES |
| Frequency(Hz) | 25.32 | 22.56 | 104.88 | 3.58 |
| Event size(kB) | 810.73 | 718.61 | 224.58 | 726.92 |
| Data Transport Rate(MB/s) | 20.05 | 15.83 | 23.00 | 2.34 |

about 8 TB of dark matter data. The performance met the challenging requirements in the search of very low energy dark matter recoil events. Although designed for PandaX-I, the same system is used in PandaX-II, the second phase experiment with a 500-kg target currently under operation [7]. The increased detector size in fact suppresses the trigger rate due to the self-shielding effects of liquid xenon, and the longer drift time does not lead to larger event size due to zero suppressions in the waveform data. This system is also expandable to the future phase of the experiment and maintains flexibility in acquisition strategy to further optimize the performance.

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References

[1] PandaX collaboration, X. Cao et al., PandaX: A Liquid Xenon Dark Matter Experiment at CJPL, *Sci. China Phys. Mech. Astron.* **57** (2014) 1476 [arXiv:1405.2882].

[2] PandaX collaboration, M.-J. Xiao et al., First dark matter search results from the PandaX-I experiment, *Sci. China Phys. Mech. Astron.* **57** (2014) 2024 [arXiv:1408.5114].

[3] PandaX collaboration, X. Xiao et al., Low-mass dark matter search results from full exposure of the PandaX-I experiment, *Phys. Rev. D* **92** (2015) 052004 [arXiv:1505.00771].

[4] Hamamatsu PMTs, http://www.hamamatsu.com.

[5] XENON100 collaboration, E. Aprile et al., The XENON100 Dark Matter Experiment, *Astropart. Phys.* **35** (2012) 573 [arXiv:1107.2155].

[6] CAEN V1724 Manual, http://www.caen.it.

[7] PandaX collaboration, A. Tan et al., Dark Matter Search Results from the Commissioning Run of PandaX-II, submitted to Phys. Rev. D (2016) [arXiv:1602.06563].