Readout electronics and data acquisition system of PandaX-4T experiment

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ABSTRACT: PandaX-4T is a dark matter direct detection experiment located in China jinping underground laboratory. The central apparatus is a dual-phase xenon detector containing 4 ton liquid xenon in the sensitive volume, with about 500 photomultipliers instrumented in the top and the bottom of the detector. In this paper we present a completely new system of readout electronics and data acquisition in the PandaX-4T experiment. Compared to the one used in the previous PandaX dark matter experiments, the new system features triggerless readout and higher bandwidth. With triggerless readout, dark matter searches are not affected by the efficiency loss of external triggers. The system records single photoelectron signals of the dominant PMTs with an average efficiency of 96%, and achieves the bandwidth of more than 450 MB/s. The system has been used to successfully acquire data during the commissioning runs of PandaX-4T.

KEYWORDS: Data acquisition concepts; Trigger concepts and systems (hardware and software); Dark Matter detectors (WIMPs, axions, etc.)

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1 Introduction

The existence of dark matter has been established by many cosmological and astrophysical observations. Detection of DM particles is the central goal of many experiments. The PandaX project consists of a series of xenon-based experiments to search for DM particles and to study the properties of neutrinos, utilizing the time projection chamber (TPC) technique. PandaX-4T is a 4 ton scale dual-phase TPC, located in the B2 hall of the second phase of China Jinping underground laboratory (CJPL-II). Particle interaction in the liquid xenon produces a prompt scintillation signal (S1) and ionization electrons which are drifted up to the gaseous xenon region. These electrons subsequently produce a delayed scintillation signal (S2). The top and the bottom of the TPC are instrumented with 169 and 199 3-inch Hamamatsu R11410-23 photomultipliers (PMTs), Two circles of 105 1-inch Hamamatsu R8520-406 PMTs are placed at the top and the bottom of the veto compartment to reduce peripheral background.

The main goal of the electronics and data acquisition system is to digitize the electrical signals from PMTs and record data that might correspond to physical interactions in the liquid xenon. With the upgrade of the detectors in PandaX, the readout electronics and DAQ system have also evolved. In previous experiments PandaX-I and PandaX-II [1, 2], the data acquisition of digitizers (CAEN V1724, 100 MS/s sampling rate) relies on global external trigger signals. The trigger system is designed to trigger on relatively large S2 signals. Upon a trigger request, the data of each channel during a fixed time window are read out with baseline data suppressed in the digitizers. The length of the window is usually set to be at least twice of the maximum electron drift time in the liquid phase, in order to make sure both S1 and S2 signals are recorded.

This global-trigger based data acquisition scheme is straightforward. A trigger defines a possible physical event. However, the sensitivities of DM searches are inevitably affected by the trigger efficiency loss. Many DM-xenon interactions, including weakly interacting massive particles (WIMP)-nucleon interactions, DM-nucleon interactions via a light-mediator, light DM-electron scatterings, and so on, produce S2 signals with a roughly exponentially falling distribution. Especially, the expected signals from light-mediator DM models [3, 4] and light DM models [5].
Table 1. Evolvement of the electronics and DAQ system in PandaX project from PandaX-I to PandaX-4T. The same system is used in PandaX-I and PandaX-II. The trigger system was upgraded in 2017, reducing the threshold from 4 electrons to 2.5 electrons [2]. PandaX-4T features a triggerless and higher-bandwidth DAQ.

| Experiment | Number of PMTs | Digitizers | Trigger and DAQ | Data transmission |
|------------|----------------|------------|-----------------|-------------------|
| PandaX-I   | 183            | V1724 (100MS/s) | Global-trigger based | Daisy chained |
| PandaX-II  | 158            | V1724      | Global-trigger based, upgraded | Daisy chained |
| PandaX-4T  | 473            | V1725 (250MS/s) | Triggerless   | Parallel        |

are more peaked towards the trigger threshold than that of the WIMP model. For example, in the light DM-electron analysis [5], the S2 lower cut is set to be the same as the trigger threshold. In this case, trigger inefficiency becomes one of the dominant causes for signal detection efficiency loss.

In PandaX-4T, the readout electronics system is designed with new digitizers (CAEN V1725, 250 MS/s). This digitizer is capable of acquiring data without relying on the global triggers. Each digitizer channel can be self-triggered independently. In this case, each self-trigger corresponds to the PMT likely being hit by scintillation lights. The data of each channel are then read out together with the self-trigger time information. Besides the new digitizer system, the DAQ system is also redesigned with improved bandwidth. In PandaX-I and PandaX-II, several digitizers are daisy chained and their data are read out via an optical link. Only one DAQ readout server is used. In PandaX-4T, data of each digitizer are read out through a separated optical link. Four DAQ readout servers are used. Data from each server are sent to another server for further processing and finally saved into the disk.

Table 1 summarizes the evolvement of the electronics and DAQ system from PandaX-I to PandaX-4T. In this paper we present the PandaX-4T electronics and DAQ system and its performance in the commissioning runs. We only discuss performance related to the dominant 3-inch PMTs.

2 Readout Electronics and DAQ of PandaX-4T

Figure 1 illustrates the overall design of the PandaX-4T readout electronics and DAQ system. The system in situ is shown in Figure 2.

The whole system consists of three main parts. The first part includes custom designed PMT signal decoupling and amplification modules. The anode signal from each PMT is transmitted to outside on the same coaxial cable which provides the PMT High Voltage (HV) bias. For future development, 14 PMTs are mounted on the new base boards [6], which have a new configuration of decoupling capacitors near the last several dynodes to extend the dynamic range and provide two readout signals at the anode and the eighth dynode. These PMTs are located in the central top and bottom PMT arrays. Their dynode signals are also transmitted to outside using coaxial cables. Each PMT signal from the anode or the dynode is separated from the HV via a capacitive decoupling circuit, which is the same as the one used in previous PandaX experiments. The decoupled signal is
Figure 1. The schematic drawing of PandaX-4T readout electronics and DAQ hardware system. See text for details.

Figure 2. The PandaX-4T readout electronics and DAQ system in situ. This system includes two VME crates for the new decouplers, one VME crate for the digitizer array, and one VME crate for servers.
then amplified through a high-speed operational amplifier (ADI AD8009). This amplifier has very high slew rate (5.5 V/ns) and large bandwidth (700 MHz, G=2 at -3dB for small signals) [7]. Thus the impact on the PMT signal shape is expected to be small. The decoupling and the amplification circuits are integrated on the same PCB module (called new decouplers below), shown in Figure 3. The amplification is configured to be 1.5 and 5 for 3-inch PMTs and 1-inch PMTs, respectively. This new design greatly reduces the complexity of the whole electronics system. In previous PandaX experiments, the decouplers and the amplifiers (Phillips 779 NIM modules) are located in different places and they must be connected through coaxial cables.

The second part includes 32 CAEN V1725 digitizers. V1725 is a 16-channel VME module. Each input PMT signal is digitized by a flash ADC channel with 14-bit resolution and 250 MS/s sampling rate. The dynamic range is configured to be 2.0 Vpp, leading to 0.122 mV for the least significant bit (one ADC count). In PandaX-4T, the typical single photoelectron (SPE) signals from 3-inch PMTs have the amplitude around 7 mV and the pulse width around 20-30 ns. An example of the digitized waveform from a SPE signal is shown in Figure. 4 left.

As mentioned in the introduction, a triggerless readout scheme is used in the PandaX-4T experiment. This is achieved by using the dynamic acquisition window (DAW) algorithm implemented in the V1725 digitizers [8]. On a channel-by-channel basis, digitized samples above a threshold can be automatically identified. This is referred as the self-trigger. Then a pre-configured number of data (before and after the trigger time) are saved into the buffer in the digitizer for readout, together with other information such as the trigger time tag and the channel number. Figure. 4 right shows a typical recorded amplitude distribution from a 3-inch PMT, with the self-trigger.
Figure 4. Left, a digitized waveform of a typical SPE signal from a 3-inch PMT in PandaX-4T. Right, recorded waveform amplitude distribution of one 3-inch PMT channel with a self-trigger threshold of 20 ADC counts.

Figure 5. The differential (left) and single-ended (right) clock fanout module used for the PandaX-4T digitizer system. The former provides synchronous external clocks for the digitizers. The latter provides synchronous start-acquisition signals and external-trigger signals.
threshold set to be 20 ADC counts. The typical amplitude of a SPE signal is about 60 ADC counts, so this threshold corresponds to approximately 1/3 PE. To ensure timing synchronization among all digitizers, common external clock signals are used. These clock signals are originated from a common clock oscillator and distributed by custom designed differential clock fanout modules (see Figure 5 left). In this way, there is no need to tune the clock phase as in the previous electronics system [1], where clock signals were daisy-chained among all digitizers. The start-acquisition of the digitizer is configured to be “first trigger controlled” [8]. The acquisition is started once receiving a pulse originated from a generic logic unit (CAEN V1495) and distributed by custom designed single-ended clock fanout modules (Figure 5 right).

In addition to the self-trigger mode, the digitizers can be configured to acquire data with external triggers. In this mode, a number of data with equal length from all channels are read out without baseline suppressions. This can be used for PMT gain calibrations and self-trigger efficiency studies.

The last part includes the data acquisition, processing, and storage. Four readout DAQ servers (Dell R730) are used to acquire data from the 32 digitizers. Each DAQ server is connected with 8 digitizers through individual optical fibers with two PCIE interface cards (CAEN A3818C). The data transfer rate is up to 85 MB/s for each digitizer. The acquired data of each server are sent to another data server (Dell R930) via a 10 Gbps optical fiber switch. In the data server, all received data are sorted according to the trigger time tag and written into disk afterwards. Raw data are transferred to a computer cluster for offline processing and analysis.

In PandaX-4T, the DAQ system is controlled via a web-based interface. Before each run, parameters such as the trigger mode (self or external trigger), self-trigger threshold of each channel, record length of each trigger, can be configured on this interface and are written into a database. After the DAQ system is started, the readout DAQ servers will configure the digitizers using the parameters from the database. The above-mentioned start-acquisition pulse is sent to all digitizers only after they have been configured, so all digitizers start to acquire data at the same time.

3 Performance

We start by showing the performance of the new decoupler modules. Using low-intensity LED calibration data, we measured the SPE charge distributions for 64 PMTs with 64 old decouplers. The same measurements are repeated with 64 new decouplers at the same condition. Figure 6 left shows the comparison of the charge distributions from one PMT. The peak around zero is the pedestal region and corresponds to electronic noise in the baseline. The second peak corresponds to the PMT response to a single photoelectron. As expected in last section, the chosen amplifiers have little impact on the charge measurement of signals. But there is a reduction in the pedestal width of 24% on average with the new decouplers, shown in Figure 6 right. This corresponds to a 32% improvement on the signal-over-noise ratio.

Then we show the efficiencies of the self-trigger threshold on SPE signals. This is one of the key parameters that affects the signal efficiency in the triggerless readout scheme. During the commissioning runs of PandaX-4T, the threshold is set to be 20 ADC counts for 3-inch PMTs. The efficiency of recording SPE signals is estimated using low intensity LED calibration data without baseline suppression applied in the digitizers. These data are recorded with 50 Hz external triggers...
Figure 6. Left, comparison of the charge distributions of one 3-inch PMT, with the new (red) and the old (blue) decoupler module. Right, the ratio of the pedestal width, measured using 64 new decouplers and 64 old decouplers.

that are synchronous to the pulse which drives the LED. So a possible SPE signal can be searched for in a fixed window of each recorded data. The resultant amplitude (in unit of PE/4 ns) of one 3-inch PMT is shown in Figure 7 left. In this plot, the raw amplitude (in unit of ADC counts) is divided by the gain of this PMT channel determined using light calibration data. Here, the gain is in unit of ADC counts×4 ns (as in Figure 7 right), where 4 ns corresponds to the sampling interval of the digitizers. The distribution is fitted with a sum of two Gaussians to describe the noises and signals, respectively. The SPE amplitude mean is about 0.39 PE/4 ns, with a relative variation of 4% among all channels. The mean values have almost no dependence on the gain. On the other hand, the SPE amplitude width varies from 0.09 PE/4 ns to 0.12 PE/4 ns as the gain increases, with a relative variation of 8-11% among channels.

The SPE trigger efficiency is estimated as the fraction of signal events above the threshold. Figure 7 right shows the obtained efficiency vs. the gain of each 3-inch PMT channel. Using the above-mentioned mean value of SPE amplitude of all channels, and the gain-dependent amplitude width, we can predict the efficiency for any given gain. This is the red curve in Figure 7 right. Taking into account the above-mentioned variations among channels, we can estimate how much the efficiencies are expected to change. This is shown as the yellow band. If we consider twice of the variations, the efficiencies vary within the green band. Overall, we can see that the measurements are consistent with the prediction. The average self-trigger efficiency of all 3-inch PMTs is 96%.

The above measurements have been used to model the S1-loss in the signal model for the first DM search [9].

Unlike previous PandaX experiments, there is no more definition of events at the DAQ level in PandaX-4T. At the DAQ level, waveform information is recorded at the channel-by-channel basis and independently among all channels. Only in offline analysis, S1 and S2 signals are identified using information from all channels. Afterwards, a physical event is built by combining S1 and S2 signals within a window of 1 ms. We use physics data to validate the DAQ. Unless otherwise stated, all data used here and below were recorded during the commissioning phase of the detector from
Figure 7. Left, amplitude spectrum (in unit of PE/4 ns) of a R11410 3-inch PMT in low-intensity LED calibration data. Superimposed function (red) is a combined fit of two Gaussian functions to model the noise (blue) and the SPE signals (green). The black-dashed line denotes the self-trigger threshold for this channel. Right, self-trigger efficiency of SPE signals vs. gain for each 3-inch PMT channel. The data points are measurements. The red curve and the bands are predictions and uncertainties using inputs from measurements. See text for details. Here, the gain refers to the mean of the integral of raw digitized waveform for SPE pulses. A gain of 100 ADC counts × 4 ns corresponds to a PMT gain of approximately $4 \times 10^6$.

Nov 2020 to May 2021. The cathode of the TPC was applied with a HV of -16 or -18 kV. The drift velocity of electrons in the liquid is about 2 mm/μs, so a maximum electron drift time of about 800 μs is expected. The gate of the TPC is applied with a HV of -5 kV to extract the electrons into the gaseous region. The measured electron extraction efficiency is above 90% [9]. Then the deposited energy in the liquid xenon from this event can be determined from the S1 and the S2 signals, together with other detector parameters including photon detection efficiency, electron extraction efficiency, the single electron gain, and other corrections [9]. Figure 8 left shows the vertex distribution of selected events with reconstructed energies between 20 and 60 keV from $^{83m}$Kr calibration data. A maximum drift time of 840 μs is observed, consistent with expectation. Figure 8 right shows the reconstructed energy spectrum which corresponds to the two conversion electrons with expected total energy of 41.5 keV from $^{83m}$Kr decays. Events with only one pair of S1 and S2 signals are selected. The event vertex is required to satisfy $R^2 < 2500 \text{ cm}^2$ and $20 \mu s < t_{S2} - t_{S1} < 700 \mu s$ to reduce external backgrounds. The S1 and S2 waveforms of one selected event is shown in Figure 9. In this event, the two S1-like pulses from the cascade decays of $^{83m}$Kr are not well separated and thus merged as one S1 signal. These results validate the electronics and DAQ system.

In PandaX-4T, the DAQ system is designed to save all self-triggered data in the digitizers to disk for offline analysis. This imposes larger bandwidth requirement compared to the global-trigger based DAQ system. A maximum bandwidth of 470 MB/s was achieved with a Pu-C neutron source placed outside the TPC during an earlier test run in 2020. During the commissioning runs, the bandwidths of most runs range from 20 MB/s to 80 MB/s, depending on the run conditions. A bandwidth of less than 100 MB/s is also preferred for two reasons. The effect of data loss due to digitizer busy is negligible as discussed below. During the data acquisition, the raw data are transferred from CJPL-II to the computer cluster in Chengdu through a 1 Gbps optical link. The
Figure 8. Left, vertex distribution of events with reconstructed energy between 20 and 60 keV in $^{83m}$Kr calibration data. Right, the reconstructed energy spectrum of the two conversion electrons with total energy 41.5 keV from $^{83m}$Kr decays.

Figure 9. A typical waveform from $^{83m}$Kr decays. The S1 signal contains two pulses. The first one corresponds to the emission of the conversion electron with energy of 32.1 keV. The second one corresponds to the 9.4 keV conversion electron, emitted following the first electron with a 154 ns half-life.
maximum bandwidth is about 100 MB/s.

![Figure 10](image)

**Figure 10.** The bandwidth of each digitizer (unit: MB/s) as a function of time during a typical background run for DM searches during the commissioning runs of PandaX-4T.

Finally, we discuss the effect of data loss due to the digitizer busy. This might cause nonnegligible systematic errors in the event reconstruction. During the background runs for DM searches, the bandwidth is only about 20 MB/s, with each digitizer contributing up to 1.5 MB/s, shown in Figure 10. The busy time of the digitizers at this level of the bandwidth is negligible, given the on-board buffer of 10 MB/channel and the readout bandwidth limit of 85 MB/s per digitizer. This is verified by comparing the reconstructed peaks of known $\gamma$ rays in background runs and calibration runs. Figure 11 shows the several high energy reconstructed $\gamma$ peaks in background runs. Here and below, the above-mentioned event and vertex selections are applied. The two peaks with largest statistics correspond to the 164 keV and 236 keV $\gamma$ rays from $^{131m}Xe$ and $^{129m}Xe$ decays, respectively. The two peak values in data are determined to be 164.32±0.02 keV and 235.92±0.02 keV. A number of runs were taken with neutrons injected into the TPC from a deuterium-deuterium (D-D) fusion source. The bandwidths range from 60 to 80 MB/s, with contribution from each digitizer up to 5-6 MB/s. The two peak values in these data are 163.8±0.1 keV and 235.1±0.1 keV. The difference compared to background runs is 0.3%. This is consistent with the 0.3% variation of the 164 keV peak values obtained in different background runs [10]. This shows that the impact of digitizer busy is negligible in these data acquisition conditions.

One run was taken with a $^{137}$Cs source placed at the DD injection tunnel. The bandwidth is
120 MB/s. The maximum bandwidth from single digitizer is 11 MB/s. The two peaks become $161.7 \pm 0.2$ keV and $233.6 \pm 0.4$ keV. The maximum difference compared to background runs is 1.6%. This illustrates that digitizer busy causes noticeable systematic effect in this run condition. Therefore, it might be useful to use the global triggers to acquire data in this case. However, due to the limitation of the digitizers, S1 and S2 signals can not be recorded in one trigger. Only data less than several $\mu$s in advance of the trigger time can be recorded. This problem can be solved with a new type of custom designed digitizers [11].

![Energy Spectrum](image)

**Figure 11.** Reconstructed energy spectrum from 130 keV to 280 keV in background runs. The distribution is fitted with a sum of three Gaussian functions to model the $\gamma$ peaks, and an exponential function to model the continous background.

### 4 Summary

In summary, we presented the electronics and the DAQ system in the PandaX-4T experiment. Waveform of each PMT is recorded if the pulse is above the threshold on a channel-by-channel basis. The average efficiency of recording SPE signals of the 3-inch PMTs is 96%. The DAQ system is designed to save all recorded data in the digitizers for offline analysis. The maximum bandwidth of the DAQ system is above 450 MB/s. This represents an improvement of more than a factor of 6 compared to the system in previous PandaX experiments [1]. Many DM searches are expected to benefit from this triggerless DAQ, since there is no more inefficiencies due to the global triggers. In the first DM search in PandaX-4T [9], the lower threshold on S2 signal is already reduced to 80 PE from 100 PE which was used in the PandaX-II final WIMP analysis [12]. The presented system has been used to successfully acquire data during the PandaX-4T commissioning phase from Nov 2020 to May 2021. Data taking will be resumed after a tritium removal campagain.

### 5 Acknowledgement

This project is supported by grants from the Ministry of Science and Technology of China (No. 2016YFA0400301 and 2016YFA0400302), a Double Top-class grant from Shanghai Jiao Tong University, grants from National Science Foundation of China (Nos. 11875190, 11505112, 11775142...
and 11755001), supports from the Office of Science and Technology, Shanghai Municipal Government (18JC1410200), and support also from the Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education. This work is supported also by the Chinese Academy of Sciences Center for Excellence in Particle Physics (CCEPP).

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