Abstract.

DEAP-3600 is a dark matter experiment using liquid argon to detect Weakly Interacting Massive Particles (WIMPs). The DEAP-3600 Data Acquisition (DAQ) has been built using a combination of commercial and custom electronics, organized using the MIDAS framework. The DAQ system needs to suppress a high rate of background events from $^{39}$Ar beta decays. This suppression is implemented using a combination of online firmware and software-based event filtering. We will report on progress commissioning the DAQ system, as well as the development of the web-based user interface.

1. DEAP-3600 Experiment

DEAP-3600 is a dark matter experiment located at SNOLAB in Ontario, Canada. The DEAP detector uses 3600kg of liquid argon to search for the interactions of WIMPs, a dark matter candidate. Scintillation light from the WIMP interactions is imaged using an array of 255 PMTs; an image of the partly constructed DEAP detector is shown in Figure 1. A critical challenge for the DEAP experiment is the large background from $^{39}$Ar beta decays which occur at a rate of 3.6kHz. These beta decays can be efficiently eliminated by pulse shape discrimination [1].

The DEAP Data AcQuisition (DAQ) system has been designed to handle the very large $^{39}$Ar event rate without compromising the detection of other interactions occurring at a much lower rate. Key features of the DEAP DAQ include: i) factor of 5 to 10 online $^{39}$Ar event rejection using a custom trigger board by analyzing 22 summed PMT waveforms sampled at 45 Mega Samples per second (MS/s) in an FPGA housed in a custom board, ii) digitization and pulse processing of the PMT signals using commercial CAEN 250MS/s FADCs, iii) data acquisition software designed using the MIDAS (Maximum Integrated Data Acquisition System) DAQ toolkit providing online pulse feature extraction and event filtering capabilities. The full DAQ is capable of providing a factor of 50 to 100 data rate reduction by filtering out beta decays during regular data taking, and is also capable of handling data rates of 200-300MB/s during calibration runs.

The following will explain the details of the DAQ and report on the current status of DAQ commissioning.

2. Overview of Electronics

In the region of interest for WIMP interactions (energy < 100 keV and center of the LAr volume), the average number of photo-electrons per PMT is expected to be less than 2.5. In order to identify individual pulses in time we require narrow pulses and digitizing at high speed. The PMT pulses are about 10 ns wide, and as a 250 MS/s digitizer is used, the pulse shape must...
be widened by a factor of 2 to 3, to optimize signal-to-noise and provide several samples on the rise time of the pulse.

![Image of the DEAP-3600 detector with PMTs bonded to central acrylic vessel.](image)

Figure 1. Image of the DEAP-3600 detector with PMTs bonded to central acrylic vessel.

Table 1 shows that in normal running, as opposed to dedicated calibration runs, the overwhelming majority of the DEAP-3600 events are $^{39}$Ar beta decays. However, it is not desirable nor useful to record billions of beta decay events, so many must be filtered out. As these events are key to testing the position reconstruction algorithms (by confirming that they are reconstructed uniformly across the LAr volume), it is important that the electronics system selects them in an unbiased way. The trigger system has been designed to be highly tunable and easy to monitor, to help satisfy this minimum bias requirement.

| Type                  | Rate (Hz) | Purpose                                      |
|-----------------------|-----------|----------------------------------------------|
| $^{39}$Ar beta decay  | 3600      | Energy and position calibration              |
| $^{222}$Rn decay      | $< 5 \times 10^{-6}$ | Decay chain identification                  |
| Cosmic muons          | $< 10^{-3}$ | Background characterization                  |
| Neutrons in argon     | $< 10^{-6}$ | Irreducible background                       |
| WIMP in argon         | $< 10^{-5}$ | Signal!                                      |
| Surface background    | $10^{-3}$  | Decay chain identification and position calibration |

Table 1. Expected data rates in DEAP-3600 during normal running.

The DEAP-3600 electronics architecture is shown in Figure 2. All of the electronics are located outside the water tank which shields the liquid argon vessel and are housed in three standard computer racks. The architecture is logically divided into 3 systems: front end, trigger and data acquisition (DAQ).

The first stage are Signal Conditioning Boards (SCBs). These decouple the high voltage, provide high voltage protection, and shape/split the PMT signal. An analog sum of the signal from all 12 PMTs on each board is sent to the Digitizer and Trigger Module (DTM), which decides whether to trigger an event. The high-gain outputs are connected to 250 MS/s CAEN V1720 digitizers [2], and the low-gain outputs are connected to 62.5 MS/s CAEN V1740 digitizers [3]. The front end system is detailed in Section 3, the trigger system in Section 4, and the DAQ system in Section 5.
3. Front end system: high voltage distribution and signal conditioning

The front end system comprises an ISEG [4] MPOD [5] high voltage supply and 26 Signal Conditioning Boards (SCBs)—22 for the 255 liquid argon PMTs and 4 for the 48 veto PMTs. The SCBs are responsible for amplifying and shaping the PMT signals. They are contained in two separate racks, with 14 SCBs in each (including one spare in each rack). All the SCBs in a rack are connected to a backplane, through which they can be controlled by a PC.

![Figure 2. Overall DEAP electronics concept](image)

Each SCB has 12 identical circuits to shape and amplify the 12 PMT signals. The first stage amplifier of each circuit is set for unity gain to provide a high impedance input so as not to disturb the 75 Ω cable impedance matching. The signal is then split into three branches: the high gain, low gain and analog sum channels. The high gain channel is designed to achieve high signal-to-noise for single photo-electrons (SPEs) and to adapt the pulse shape to the 250 MS/sec digitizer. The low gain channel is designed to shape pulses that saturate in the high gain channel. The PMT signal is stretched and attenuated by a factor of 10 in amplitude going through the low gain channel. The pulse shape is widened in order to allow digitizing at 62.5 MS/sec rather than 250 MS/sec, which has a factor of 5 cost saving.

The final branch from each 12 PMTs in an SCB is added together to make an analog sum of the twelve channels. This analog sum is used for the online triggering (described in Section 4) and hence control of noise is very important on this branch. The summed signal from each SCB is passed through the SCB backplane, and connected to the DTM with a 24 channel differential connector.

4. Trigger system

The Digitizer and Trigger Module (DTM) is responsible for making the trigger decision (primarily by digitizing and analyzing the 22 analog sums from the SCBs, though other trigger modes are supported), providing the master clock to all the digitisers (to ensure all boards are synchronized), and for preparing the digitized analog sum waveforms to be read by the DAQ system (to allow monitoring of the data used to make the trigger decision). Secondary functionality provided by the DTM includes triggering the test pulse injection system, external calibration device triggering, accepting external triggers from the veto and calibration devices, software triggering, and throttling data collection if the DAQ is busy. The busy system is explained in Section 5.
Figure 3. Schematic of the different $E_{\text{short}}$ and $f_{\text{prompt}}$ regions for the physics trigger, which allows for different pre-scaling and different hardware to be read out for events in each region.

The trigger system includes a separate Pulse Pattern Generator (PPG) board, which can emit a programmed pattern of pulses when it receives a signal from the DTM. The PPG signal is passed through a fan-out board and distributed to a test input port on all the SCBs. The SCBs then distribute this signal to all channels. This system allows for simulating a PMT signal even if the PMTs are not connected or powered.

The DTM hardware is based on a custom TRIUMF-designed 6U VME motherboard populated with an ALTERA Stratix IV GX FPGA. The motherboard has three daughter mezzanine boards connected through FPGA Mezzanine Card (FMC) [6] standard connectors: a 24-channel ADC card consisting of three 8-channel 12-bit 50 MHz ADC chips [7]; a 12-channel NIM I/O card with 8 outputs and 4 inputs; and a master clock distribution board, providing 62.5 MHz clock distribution to the DAQ system. The DTM control code and event selection algorithms are implemented in custom-written VHDL firmware, which can be updated remotely through the VME connection.

The trigger logic is based on a set of trigger sources and trigger outputs, which are mapped in a many-to-many relationship. A trigger source decides whether an event should be triggered, based on either internal or external information. A trigger output decides which hardware devices should receive the trigger signal and whether the event should be pre-scaled. Pre-scaling means that a configurable percentage of triggers are ignored, for example to reduce the trigger rate of events that look like $^{39}$Ar beta decays. The trigger sources, trigger outputs and the mapping between them are all configurable for each run.

The main DTM physics trigger is designed to accept events in the WIMP region of interest with 100% selection efficiency, while reducing the acceptance of $^{39}$Ar beta decay events. The DTM performs rolling integrals of the sum of the analog sums of groups of 12 channels in two time windows (nominally 300 ns and 1600 ns), aligned to the same start time. The total energy in the narrow window ($E_{\text{short}}$) and the ratio of energy in the narrow and wide windows ($f_{\text{prompt}}$) are calculated. The ($E_{\text{short}}$, $f_{\text{prompt}}$) phase space is split into 6 regions, as shown in Figure 3. Very low events are discarded completely, as they are likely to just be noise. The other 5 regions are all mapped to different trigger outputs, allowing for different pre-scaling and for different hardware to be read out for events in each region. In the medium energy region, WIMP candidates will have high $f_{\text{prompt}}$ and will not be pre-scaled, while beta decays will have low $f_{\text{prompt}}$ and will be pre-scaled. In the low energy region, there is more overlap between the distributions, so the pre-scaling requirements are different. The boundaries of each region are
configurable, and can be optimised while the detector is being commissioned.

For each trigger source that fires, any trigger outputs that are mapped to it are examined. Trigger signals are sent out through the NIM I/O outputs to whichever hardware is defined for that trigger output. This is a very powerful and flexible system that can be used to create complex trigger conditions during normal running that keep 100% of WIMP-like events, while drastically reducing the data rate of background events. The system also supports completely different and configurable trigger conditions for calibration runs, and the settings can be easily changed using software and web interfaces.

5. Data acquisition system: digitization, filtering and event building

The Data Acquisition (DAQ) system includes the digitisers and readout system. To complement the hardware-based trigger, the DAQ includes a software-based online filter, which analyzes the V1720 digitizer data to refine the decision about which information should be saved for each event.

The DEAP-3600 DAQ is built using the MIDAS software framework [8]. MIDAS provides a simple, but powerful framework within which to construct a complicated DAQ. Frontend programs (written in C/C++) communicate with various types of hardware and transfer data to buffers using a custom RPC layer. An Online DataBase (ODB) is used to store configuration information for the frontend programs, data logger and web server. Most user interface with MIDAS happens through webpages served by the MIDAS web server. There is a default web interface, but MIDAS also provides tools for creating custom web interfaces of arbitrary complexity and polish (as will be shown in Section 6).

The digitizers used are 250 MS/s CAEN V1720s (8 channels, 12 bits) and 65 MS/s CAEN V1740s (64 channels, 12 bits). The digitisers are readout through optical links using a CAEN proprietary protocol that relies on optical to PCI-express A3818 cards [9]. Each A3818 provides 4 optical links, and two V1720s are daisy chained on an optical link, so each A3818 readouts 8 V1720s or 4 V1740s. Each A3818 card is housed in a separate PC. Front end programs running on the PCs control and readout the digitizers. Further front end programs running on the PCs control and collect information from other hardware, including the DTM, veto V1740 and calibration hardware. The information from the front end programs is transferred to a master PC through a 1 Gb/s ethernet router for event filtering and event building. A logger program running on the master PC is responsible for compressing and saving the data to disk.

The V1720s can store data either in Zero Length Encoding (ZLE) mode or as raw waveforms. The ZLE algorithm runs in the V1720 FPGA, and records data only if a given number of consecutive samples exceed a threshold ADC value. Extra samples from before and after the region exceeding threshold are also saved. The threshold is set to be 5 ADC below the baseline of 3900 ADC , which is low enough to record the vast majority of single photo-electron pulses, whilst not being triggered by noise fluctuations. Using ZLE mode reduces the average event size by at least a factor 10 for a typical DEAP-3600 event, and for regular physics running the V1720s will always operate in ZLE mode. There are four V1720 front end programs, each running on a separate PC and controlling 8 V1720 modules. Each program calculates the time and charge (QT) of the ZLE pulses, and this QT summary information is passed to the master PC along with the V1720 data.

The V1740s do not use a ZLE algorithm, and only the raw waveforms can be readout. As the low-gain V1740 information is only necessary for pulses where the high-gain waveforms read by the V1720s has saturated, the V1740s do not need to be readout for every event, saving a significant amount of data throughput. Whether the V1740 data is read or not is determined by the DTM.

Each MIDAS frontend program sends its data fragments over an ethernet network to the master PC. In order for the backend application (the event builder) to collect all the fragments,
each frontend sends its data to a dedicated memory buffer. The multi-threaded event builder scans all these buffers in parallel, and extracts the individual fragments. In the first stage, it extracts the QT fragments and processes them to make a decision on the overall quality of the event (QT filtering). Its decision defines the final composition of the event sent to a final SYSTEM memory buffer, and in particular whether the full ZLE waveforms are sent, or just the QT summary information. The event builder also uses the timestamps stored in each event fragment in order to confirm that the correct fragments are being assembled. This protects against situations where a particular bit of hardware didn’t register a trigger that was sent.

The final SYSTEM buffer becomes the data source for other MIDAS applications, including the data logger which writes events to disk, and the online analyzer which processes the full event and displays diagnostic plots to help operators understand the data that is being recorded in real time (see Section 7).

Many tests have been performed to understand the data throughput bottlenecks in the DAQ system. The CAEN optical links can supply 320 MB/s to each PC, and the gigabit ethernet connections between the five front end PCs and the master PC can transport approximately 80 MB/s each, for a total of 400 MB/s arriving to the master PC. Data can be written at 345 MB/s over the NFS connection to the data disk; the disk write speed is the bottleneck in the system. This corresponds to an event rate of 200 Hz for 16 µs raw waveforms, although the V1720s will mostly be run in ZLE mode. In ZLE mode we have run the DAQ with trigger rates up to 1.7kHz for calibration and commissioning. In normal running, however, the software-based event filter in the master PC will reduce the data rate written to disk to an easier 5 MB/s.

The DAQ also includes a busy system, to throttle data collection if the event rate or data rate is too high. The V1720s, V1740s, DTM and event builder all have internal buffers to store event information, and if any of these become 50% full, the DTM receives a busy signal. When the busy signal is active, the DTM will not trigger the digitizers when a trigger source is fired. However, the DTM will always store information about each trigger time and trigger source, even if the system is busy. The buffers can start to fill if any part of the DAQ fails to keep up with the current data rate, so this busy system allows the DAQ to cope with a wide variety of issues. Trigger signals are issued again when the buffers start to empty, and the number of events that were missed while the system was busy is recorded. In normal running, the trigger conditions will be tuned so that the system does not become busy, so that a WIMP-like event is never missed. The busy system will be relied on for high-rate calibration and commissioning runs.

The combination of busy system and event building has been extensively tested in the last couple of months using a variety of high data rate test runs. The behaviour of the DAQ is
complicated: there are a variety of intermediate buffers that must fill up before the DTM starts getting the busy signals and throttling the triggering of the digitizers. But the system has proven to be robust to this complicated evolution, as well as showing a clean recovery as the trigger rate drops during a run.

6. DAQ User Interface

As the DEAP-3600 detector is located 2 km underground in an active mine, the DAQ is designed to use reliable hardware with remote operation capabilities. MIDAS provides an easy solution to manage, operate and remotely monitor the experiment over a long running period.

The DAQ system can be run remotely, with most tasks performable through web page interfaces. Examples of DAQ web pages are shown in Figures 4 and 5. The first web page shows an overview of the current trigger setup, and provides links to let the operator change the trigger settings. This allows a simple way of visualizing the complicated set of parameters needed to configure the many-to-many DTM trigger algorithm.

The second web page shows the run control interface, which allows the operator to start and stop runs. When starting a new run, a run type is chosen, which defines a standard set of trigger settings and hardware settings to use. These settings are saved in a CouchDB database [10], with a separate document for each run type. When the run is started, the saved settings are applied to the online database (ODB). Frontend programs look in the ODB for the settings that should be used for this run, and they then configure the hardware appropriately. The ODB also allows for programs to periodically write status information, which provides a history of PMT voltages, rack temperatures, and other information that is not saved in the main data stream. This system for integrating a CouchDB configuration database with MIDAS has already proven to provide an simple and error-proof way for users to set very different running configurations.

7. Online Monitoring

The final piece of the DEAP DAQ is the online monitoring. Online monitoring is the set of programs that provides users with immediate feedback on what the state of the current data being read-out. It does this by using a TRIUMF-developed package called rootana that allows C++ programs to interface with the main MIDAS online buffer. Using this functionality we have written a ROOT-based GUI that allows the user to immediately check the current digitized waveforms for a single channel or look at more sophisticated plots in order to quickly identify

1 The web interface also allows the possibility to update the settings for a particular run type in CouchDB.
and fix problems. A separate rootana program is used to monitor the PMT dark noise rates; if this program detects that the PMT dark noise rate is too high, the PMT high voltage is automatically ramped down.

In the longer term we are investigating having our rootana programs export their data via JSON to web pages, instead of having to maintain X11 GUIs. Having the data exported to web pages will allow greater flexibility in building user interfaces and easier access to the information for users. The newly added THttpServer in ROOT seems like a promising candidate for adding this functionality to our DEAP online monitoring.

8. Conclusion
DEAP-3600 will make world-leading advances in the search for WIMP dark matter candidates. One key challenge of DEAP-3600 is dealing with the high rate of $^{39}$Ar decays. The solution is continuous fast waveform digitization, with intelligent firmware and software-based triggering. The online triggering will exploit the difference in pulse shapes between $^{39}$Ar and WIMP candidates.

The DAQ system has been built with the up-to-date MIDAS framework. The frontend programs and event builder have been tested with the high data throughputs in mind; we have commissioned the system with data rates of up to 345MB/s. Using the new MIDAS web functionality, we have provided a clean web interfaces for DEAP users.

References
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