The Data Acquisition Architecture for the "Dark matter Experiment using Argon Pulse-shaped discrimination" - DEAP-3600 -

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Abstract– **This paper describes the Data Acquisition (DAQ) architecture for the DEAP-3600 experiment at SNOLAB in Ontario, Canada, which is searching for Weakly Interacting Massive Particles. (WIMPs). The identification of the WIMP is based on the rejection by signal discrimination of the beta decays from the liquid ^{39}Ar composing the detector volume (3600kg). The Data Acquisition is based on commercial electronics modules for the waveform acquisition and custom electronics for the trigger decision system. The software layer (Midas) handles the overall experiment data taking process, and the monitoring of the experimental parameters.**

I. Introduction

T HE DEAP experiment is taking place at the SNO underground laboratory (SNOLAB) near Sudbury in Ontario, Canada [1]. A spherical transparent Acrylic Vessel (AV) - 85cm inner radius, 5cm wall thickness - holds 3600kg of Liquid ^{39}Ar and makes up the detection volume (Fig 1.) The inner surface of the AV is coated with tetraphenyl butadiene wavelength shifter to shift the ultraviolet (UV) to visible light. This acrylic sphere is surrounded by 255 8" Hamamatsu R5912 PMTs pointing inwards, mounted on 50 cm long, 8" diameter light guides. The Argon is maintained in liquid state through thermal insulation and a cryogenic system in the neck of the detector [2]. The vessel - including the 255 PMTs and insulation material - is encapsulated in a Stainless Steel hermetic spherical vessel and submerged in a water container equipped with additional PMTs acting as external particle rejection detector (Fig 2.) The Data Acquisition system maintains control and monitoring of the conditioning and digitization of all PMT signals, the on-line trigger functionality and the recording of data to permanent storage.
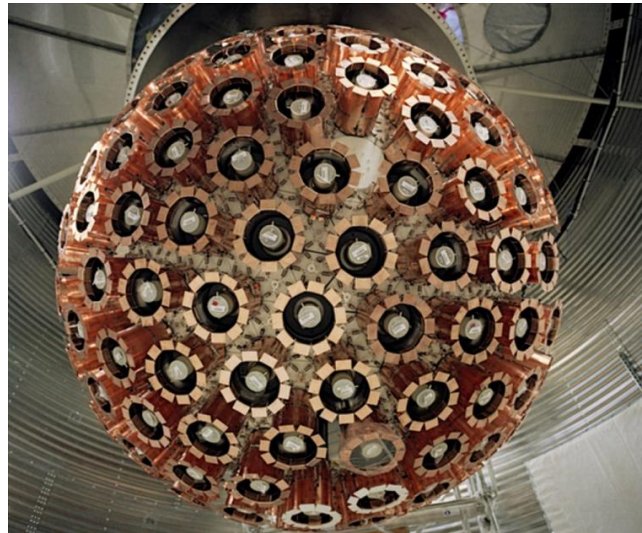

Fig. 1. DEAP detector sphere with 255 PMTs. Visible the PMTs and heat transfer Copper pads.
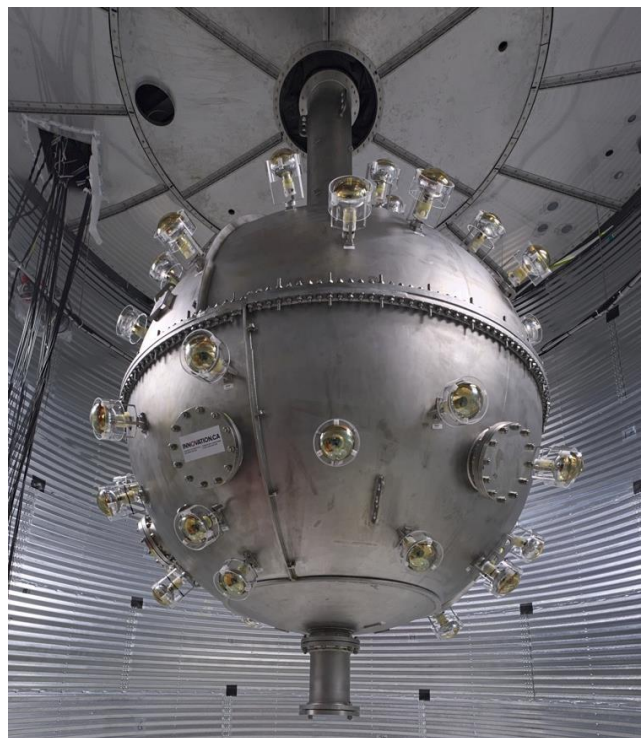

Fig. 2. Water cylinder (empty) with the Stainless Steel Vessel containing the DEAP detector in its final resting place showing veto PMTs on the outer shell.

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II. DATA ACQUISITION REQUIREMENTS

The major challenge in this experiment is the suppression of the large background from the ^{39}Ar beta decay (Table I). Fortunately the timing signature of the electron recoils from beta decay is different from the nuclear recoils of the WIMPs and neutron background (Fig 3). This characteristics permits a first in-line stage reduction of 5 to 10 by beta decay rejection using pulse shape discrimination. This initial filtering is the task of the Deap Trigger Module (DTM) discussed later on.
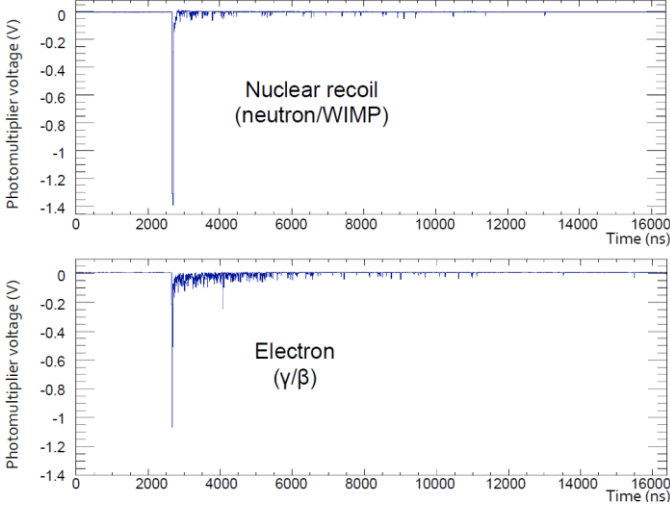

Fig 3. Typical signal signature for nuclear recoil and electron recoil.

On-line software analysis in the "Event Builder" reduces the average trigger rate by another factor of five limiting the incoming data rate to a maximum of 5 MB/s.

Event type	Rate [Hz]	Purpose
^{39}Ar beta decay	3600	Background
^{222}Rn decay	< 5E-6	Background
Cosmic muons	< 1E-3	Background
Neutron in Argon	< 1E-6	Background
WIMP in Argon	< 1E-5	Signal
Surface background	< 1E-3	Background

Table I. Expected rate of possible processes

III. ONLINE EVENT FILTERING METHOD

The total light deposition (energy) in the active detector volume has to be evaluated for the two decay time windows expected from the electron and nuclear recoils. The ratio of the sum of the energy of these windows is plotted against the Energy in the short time (prompt) window E_{short} and gives a mean of identifying the recoil reaction types.

$$F_{prompt} = E_{short} / E_{long}$$

The WIMP being expected to show in the mid-energy region of the upper half of the Fig. 3.
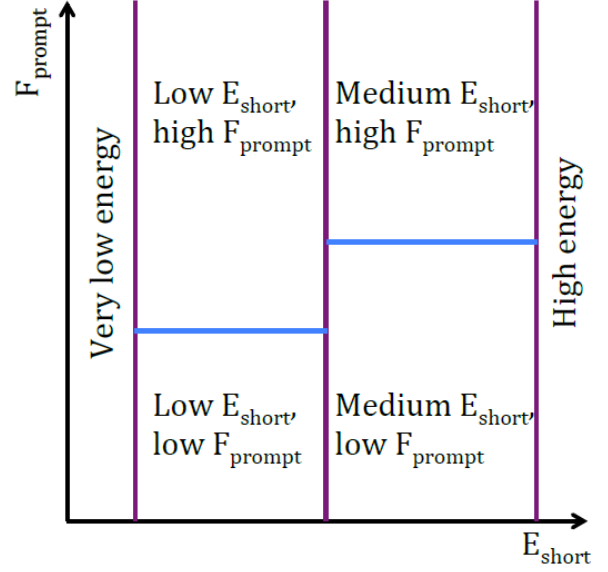

Fig. 4. Physics trigger regions used by the DTM for event triggering

The in-line hardware and software event filters use similar rejection methods and criteria which are based on the Physics trigger regions. The in-line hardware filters coarse raw ADC data using analog sums, (Fig 4.), while the software event builder uses data acquired from the full event data set.
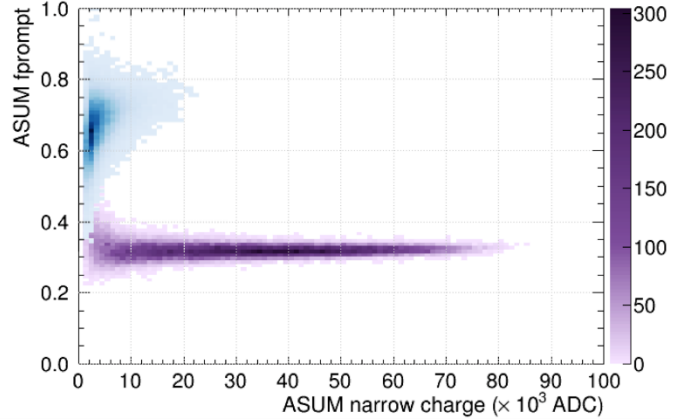

Fig. 4. DTM ASUM charge discrimination

IV. DATA ACQUISITION ARCHITECTURE

The general data acquisition layout (Fig 5.) shows the acquisition concept starting with the PMT's HV power supply feeding the Signal Conditioning Boards (SCB) which route it to the detector PMTs and the Veto PMTs. The PMT' signals are extracted on the HV lines by capacitive decoupling. The SCBs signal outputs are fed to individual waveform digitizers (WFD; CAEN V1720 and V1740). Several back-end computers (deap01..05), simultaneously acquire data from the WFDs. After pre-processing, these data fragments are forwarded to the main data acquisition machine (deap00) and assembled into global events by the Event Builder. A local network switch provides the common interconnect between the multiple network based equipment (power supplies, UPS, CDU, KVM, auxiliary systems, etc). Data from the main

WFDs are routed directly to the main acquisition machine, bypassing the LAN switch, to ensure the best response time and data throughput. The assembled data is then sent directly to data storage through a dedicated NFS 10Gb link.

A custom VME module the "Deap Trigger Module" (DTM) requires access to the data output of the SCBs in order to perform the first stage trigger filtering and to provide the trigger decision to the rest of the system. The data collected from that module is read out through a dedicated VME processor (lxdeap01) and is combined with the overall data assembly in the main DAQ machine (deap00).

The external access to the system is protected by a gateway firewall accessing the local DEAP network switch.
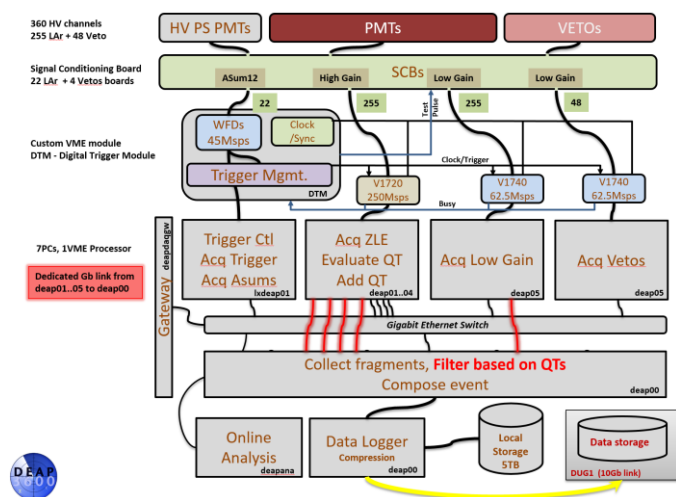

Fig. 5. Overall DEAP DAQ architecture

In more detail the different components are:

A. SCB – Signal Conditioning Board

The 255 PMTs signals are routed from the Vessel to the SCBs in the DAQ racks. For space restriction into the neck, the PMT signal is extracted from the High Voltage feed to the PMT. The SCB combines HV electrical circuit feed to the PMT and capacitive decoupling of the signal in 3 separate shaping and amplification circuits:

a) High gain to fast digitizer path (small signal).
b) Low gain to slower digitizer path (large signal).
c) Low gain analog sum of 12 consecutive channels for trigger purpose.

The SCB's are accessed for individual channel enabling and monitoring of voltages, currents, and temperatures parameters.

B. WFD – Waveform digitizers

Two types of commercial Waveform Digitizer units from CAEN have been selected the 8 channels V1720 for the 255 high gain signals sampling at 250Msps and the 64 channels V1740 for the 255 low gain signals sampled at 62.5Msps. While these units reside in a VME crate, the optical data link available on each of the module has been a key factor for its selection in addition to its interesting functional characteristics and trigger configuration schemes. Custom firmware features have also been added by the manufacturer at our request to

satisfy our implementation. The option of daisy-chaining the optical links along with the quad port transceiver interface to the acquisition computers (CAEN PCIe A3818) are valuable features and permit the optimization of the overall data network layout. In our case, as seen in Fig. 5 each computer handles one Quad-optical transceiver with each optical link handling 2 daisy-chained V1720. Data from eight V1720 modules is acquired and processed by one X86, a quad-core computer. The V1740 (4 units) are readout through individual optical links on a single X86 machine (deap05).

C. DTM - DEAP Trigger Module

The first stage of the trigger is performed by custom hardware receiving the analog sum signal of the 22 SCBs (ASUM). This custom hardware is the VME module hosting 3 separate FMC mezzanines.

a) 22 channels of pipe-lined 12bit ADC running at 45Msps.
b) Reference clock generator (62.5MHz)
c) I/O section (Single Ended: 4 Inputs, 8 Outputs)

The DTM serves multiple functions:

a) Digitizes the 22 SCB's ASUM channels.
b) Analyzes "on-the-fly" the 22 digitized SCB's ASUMs to make a trigger decision based on the physics parametric requirements.
c) Manages the different implemented trigger types such as external calibration, test pulse, and internal physics triggers. All of them have parameters such as pre-scaling, delay and trigger output mask (fragment selection).
d) Generates trigger information associated with the issued trigger. This information is composed of the trigger time stamp (used as a time reference), trigger counters, requested trigger mask, issued trigger mask, and operation status registers content.
e) Distributes the trigger signal to the acquisition modules. The dedicated I/O mezzanine on the DTM propagate physically the issued trigger to the different hardware modules. A total of 8 outputs are available. They corresponds to 4 V1720, 2 V1740, Veto, and Calibration.
f) Accepts busy signals from the WFDs for trigger throttling. All the digitizers have the capability to produce a hardware signal when their internal buffers reach a specified occupancy level. This signal is combined across all the WFDs with controllable logic to feed back to the DTM as a single busy signal. This signal throttles the DTM generated trigger output.
g) Provides the reference clock to all the acquisition hardware modules. The clock generator on the DTM provides the reference clock to all the appropriate modules. The overall number of WFDs for DEAP is 38 modules plus test pulse and auxiliary modules. This clock fan-out is provided by three low jitter circuits which guarantee consistent phase and delay to each module.

The DTM implements in its firmware several triggers (Table II) and provides 32 generic trigger output configurations. This scheme makes the triggering of the hardware very flexible.

Trigger Type	Number of Channels	Parameters
ADC FIFO	1	ADC threshold
Periodic pulser	2	Enable, Rate
Exponential pulser	5	Enable, Rate, Seed
External	3	Enable (external Inputs)
ADC Trigger	1	Windows (Energy, Time)
Minimum Bias	1	ASUM windows

TABLE II. TRIGGER TYPE AVAILABLE FROM THE DTM.

The main physics trigger (ADC Trigger) contains all the necessary parameters for the F_{prompt} decision. Example is shown in the Fig 6.

Fig. 6. Example of the DTM ADC trigger configuration from the Online Database within the Midas DAQ system.

With any of the trigger types, up to 32 trigger outputs can be configured to work simultaneously. Each output requires:
a) One of the possible trigger types.
b) Output mask defining which equipment will receive the trigger.
c) Delay time before sending the trigger.
d) Pre-scale factor for that trigger.
e) Flag that defines whether to save DTM ADC waveforms for that trigger.

Fig. 5 shows a valid trigger configuration web display. The output mask defines what hardware equipment will be involved for that particular trigger type.

Fig. 5 Web display of the overall trigger settings. It combines multiple sources such as the test pulse, 2 physics trigger at different pre-scales and 2 calibration sources. The output mask reflects what equipment will be triggered for each of them.

D. Acquisition Hardware

Each type of acquisition hardware requires a dedicated software application retrieving the information from it.
a) DTM: Trigger information and ASUM waveforms
b) V1720: High gain waveforms of the 255 PMTS
c) V1740: Low gain waveforms of the 255 PMTs
d) V1740: Veto waveforms of the VETO PMTs
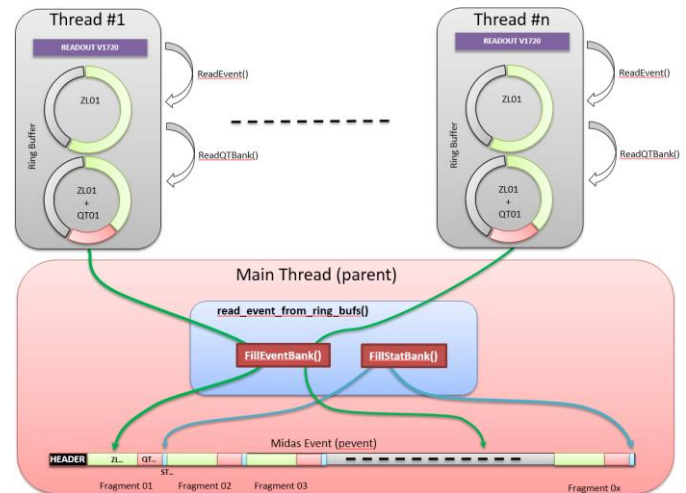e) V1720: Calibration waveforms from PMTs calibration.

Fig. 7. Frontend thread data assembly. In the DEAP case, 4 threads are started, each responsible for 2 V1720 readout modules. The thread is also appending information to raw data with summary information (QT) pertinent to the Event Builder during the overall event assembly.

For high data throughput and performance, a collection a front-end software applications are distributed across 6 computers. Each of these frontend tasks collects a fragment of the overall triggered event. They also provide additional pre-processing of their own fragment before being transmitted to the event builder.

E. DEAP Software

The overall acquisition is governed by the MIDAS Data Acquisition system [2]. MIDAS is a general-purpose software

package for event-based data acquisition in small and medium scale Physics experiments. It is presently used in major experiments such as MEG [4], T2K [5], ALPHA[6]. This software provides a clean framework for control, configuration, running and monitoring of physics experiments.

1) Frontend task

The Midas "frontend" task - code responsible for acquiring the physical data from the hardware - starts the necessary acquisition threads and reassembles the overall fragment, event-by-event. For a given event fragment, the frontend is handling multiple hardware modules. For throughput reasons, the readout function is split into multiple threads, in which readout, time stamp correlation across modules and WF feature summary extraction are performed. The main thread (parent) is performing the fragment re-assembly and the fragment transmission (Fig 7.) The synchronization mechanism for the fragment collection from the multiple threads in the main thread is managed with an atomic counter available within the C++11 compiler.

A typical running frontend tasks goes through the following sequences:
a) Thread level: Poll the hardware for data. This polling is done by individual threads, therefore the readout implementation is simpler and faster compared to a possible interrupt mechanism.
b) Thread level: Acquire the data from the hardware module. This uses proprietary DMA channels through the optical links (CAEN).
c) Thread level: Extract summary information from acquired data (charge and Time of each WF structure). Customized code scans the incoming raw data and computes the pulse timing and charge for every pulse of each WFD channel acquisition time window.
d) Thread level: Append summary data to the raw data ring buffer thread.
e) Main thread level: Do sanity check while collecting data from the different ring buffer threads. This assembly is based on polling the atomic thread counter (semaphore equivalent).
f) Transmit the event fragment to the backend computer (Event builder).

2) Event Builder task

All the fragments sent by the frontends will reach the event builder (EB) application running on the backend computer. Its main task is to re-assemble the overall event based on the similar time stamp of every fragment. In our case, the standard approach of using the trigger number is not applicable because the generated DTM trigger type can involve a sub-set of different acquisition hardware (for instance, sometimes the DTM will trigger the V1720s, but not V1740s) and therefore the trigger number is not common to all the fragments to assemble.

The event builder structure is very similar to the frontend task discussed above in the sense that multiple threads are created and each one handles the readout of a given fragment instead of the actual hardware data in the case of the frontend. The final event assembly requires several steps to ensure that the correct fragments are merged together. As the DTM is the trigger generator, it has to provide in its fragment, the reference information regarding the expected composition of the event, including the trigger time stamp and fragment list expected for this event, etc. Therefore, this fragment is decoded first and its time stamp used for fragment time matching and assembly of the event.

The typical event builder sequence, once the threads are created is:
1) All threads: Poll for fragment and place them in dedicated fragment ring buffers
2) Main thread: Poll for DTM fragment first, extract time stamp and fragment list (trigger mask).
3) Main thread: Poll, and check time stamp of involved fragment against DTM time stamp for data validity.
4) Main thread: Extract summary information (QT) from involved fragment (fragment list).
5) Analyze overall QT and make decision for final event composition.
6) Assemble final event using fragment list
7) Further information from the event builder can be appended to the event itself.

The assembled DEAP event is then sent to the MIDAS core system for dispatch to multiple data consumers. The main consumer is the data logger which directs the whole data stream to a permanent storage system. Several other consumers are "peeking" at the online data stream for analysis purposes. These tools provide the essential monitoring information regarding electronic equipment environmental condition such as PMT voltage and current monitoring, power consumption, temperature monitoring, etc, and data acquisition performance, operation stability and data quality and reliability (background rates).

Fig 8. shows the Midas web status display with 32 clients connected to the experiment. An additional analysis computer is present (deapana) to perform ROOT analysis or specific equipment data analysis.
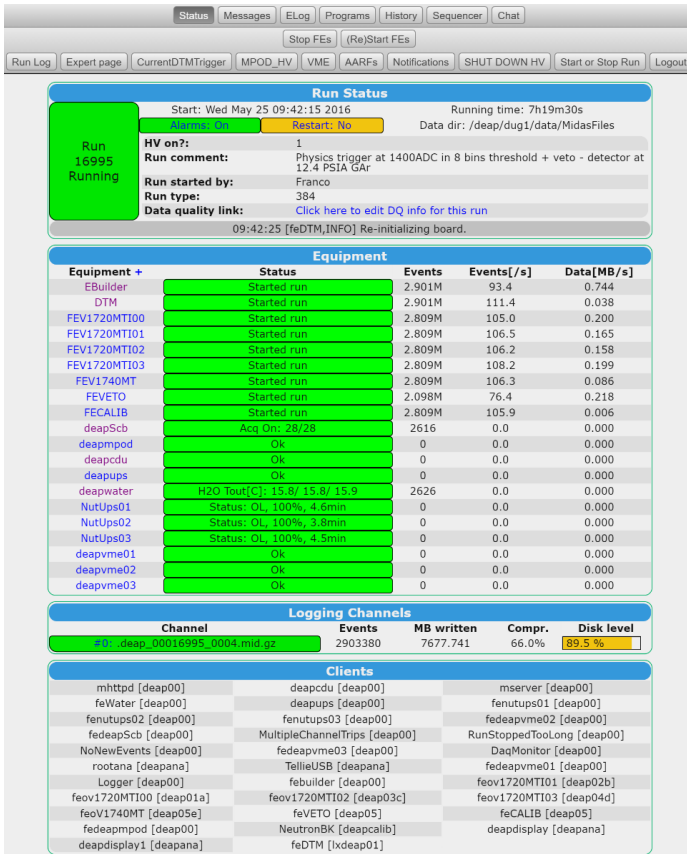
Fig. 8. Midas web display of the Experiment status. From top to bottom, standard default buttons for run operation, custom buttons for specific actions, current run information with comments, list of active frontends (green) acquiring or monitoring the experiment, logging channel information, client list currently connected to the experiment.

V. EXPERIMENT AND DAQ CONTROL

The DEAP experiment operation is subject to multiple operation constrains such as: its location in an active Nickel mine with its restricted accessibility and operation, its cryogenic systems operation, electrical and safety operation rules, etc. All of them have some impact on the Data Acquisition infrastructure. Regular blasting (mine operation) generate micro particles that have been detected on the electronics and potentially causing electrical faults. Therefore the all the DAQ equipment is installed and operated in 3 sealed racks with dedicated internal water/air heat exchangers. Underground electrical services are subject to sudden interruptions. For that purpose, we installed dedicated UPS from TRIPP LITE (SUINT3000 & 1500RTXL2U) with double-conversion function improving dramatically the quality of the AC power line. To improve the power distribution, we operate at 208VAC. Custom UPSs monitoring software is configured such that the system will partially self-shutdown within a few minutes of the power loss in order to maintain and preserve the essential electronics components for several hours and facilitate the restart of the system. This shutdown operation is possible with the addition of a Cabinet Distribution Unit (CDU) from ServerTech (CWG-16H2A454), with 16 network controlled AC ports serving all the main electronics equipment. This shutdown sequence is

particularly important for the High Voltage units (WIENER MPOD crate) powering the PMTs, as the access to the PMTs for replacement is unlikely to happen for several years. Additional high voltage protection is in place for detecting abnormal PMT's current and possible light leaks. Light leaks detection is based on PMT noise rate increase. These rates are computed by a dedicated online analysis task, which triggers a ramp down of the high voltage in case of excessive pulse rate on any PMT. This protection mechanism requires the DAQ to be fully operational. In case of a loss of the data acquisition or event analysis, here again, automatic HV ramp down procedure will kick in (Fig 9). We also installed a KVM from ATEN (KH1508Ai) connected to all the computers for network console access in case of boot problems. Besides power loss management and possible computer issues, additional DEAP DAQ operation safety requires a shift person to be logged into the DAQ system. Lack of network connection to their station will trigger a shutdown of the PMTs high voltage as well.
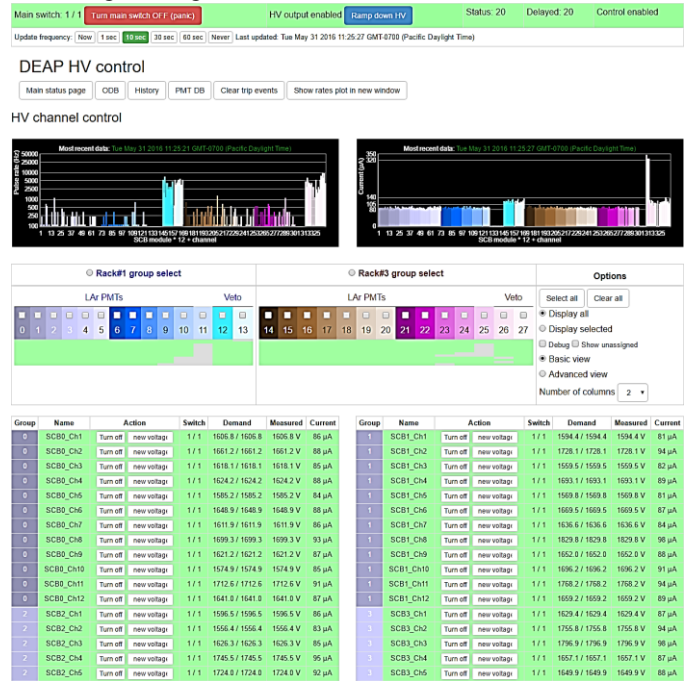

Fig. 9. Web display for High Voltage control with rate monitoring for the overall 320 high voltage channels of the experiment.

The Midas system provides a flexible alarm notification system, through which, Email, SMS and other standard notification are possible. Such a system is fully implemented for the DEAP experiment to keep the experimenters informed of the current status of the experiment (Fig 10).

Fig. 10. Web page for notification settings. SMS or notification to cloud-based team collaboration tool.

While experimental configuration is kept in the Midas online database during the active run period, the DEAP experiment keeps an overall record of all the run configurations in a CouchDB database. One of the DAQ operations is to publish at the end of each run a sub-set of information to CouchDB. The same database holds detector specific information relevant to the simulation tool and off-line analysis. A very valuable custom web tool using the CouchDB information is available to configure the entire data acquisition hardware for a particular run type. This operation requires modifying multiple fields of the Midas online database which reduce substantially the run setup time and prevents human errors in the process. Custom web page within Midas has been improved with common JSON format and JS scripting interface to the Midas system. This provided a flexible method to trigger specific functions from the standard Midas web interface (Fig 11).

Fig. 11 Run control with run type selection provided by CouchDB.

VI. DAQ PERFORMANCE

The two mode of acquisition (physics, calibration) have different event and data rate requirements.

A maximum data rate of 5MB/s for the physics runs can easily be achieved with the system when the hardware is switched in compression mode (CAEN "Zero Length Encoding", ZLE). The event size is reduced to about 8KB, the event rate is then limited by the overall frontend acquisition around 4500Hz. In the case of the calibration, the uncompressed WF are usually saved. In this case the limitation are due to frontend Ethernet link (1Gb), Data compression in the Data logger or write access to the Data storage. We do hit the network limitation first around 80MB/s between the deap01..05 to the deap00 backend machine. The Midas data logger has been extended to support lz4-compression algorithm [7], which reduces the CPU usage (in our case single thread) at the cost of ~10% loss in compression which is acceptable and permit the recording around 250MB/s for 500Hz of trigger. Further investigation is plan to raise this data rate limit.

Other specific Midas terminology figures related to the DAQ configuration:

Average number of Midas banks per assembled event: 65
Number of Midas "equipment": 20
Concurrent number of Midas client: ~30

VII. CONCLUSION

The Data Acquisition has been designed with several key points in mind:

a) Full remote operation: This has been successfully verified over the last 2 years as international collaborators have been remotely participating to the data taking.

b) Data throughput distribution and CPU load balancing across the DAQ system: This has been achieved by selecting hardware allowing us different data link scheme. Using dedicated network interface and the flexibility of the overall DAQ software configuration.

c) High data throughput requirement during calibration runs: Using dedicated network links from the frontend to the backend machines, we moved the data transfer bottle neck to the actual Ethernet 1Gbit limitation per frontend machine in the case of full waveform are recording. The maximum trigger rate is then limited to a few hundred Hz when the whole 255 waveforms are recorded.

Currently (June 2016) the DEAP detector is in its cool down phase. Data taking is continuing with Argon gas data and calibration data. The AV is expected to be filled with Liquid Argon within a couple of months.

REFERENCES

[1] http://deap3600.ca/
[2] https://arxiv.org/abs/1410.7673
[3] http://midas.triumf.ca
[4] http://meg.icepp.s.u-tokyo.ac.jp
[5] http://t2k-experiment.org/
[6] http://alpha.web.cern.ch/
[7] https://midas.triumf.ca/elog/Midas/854