FADR: The Data Acquisition System

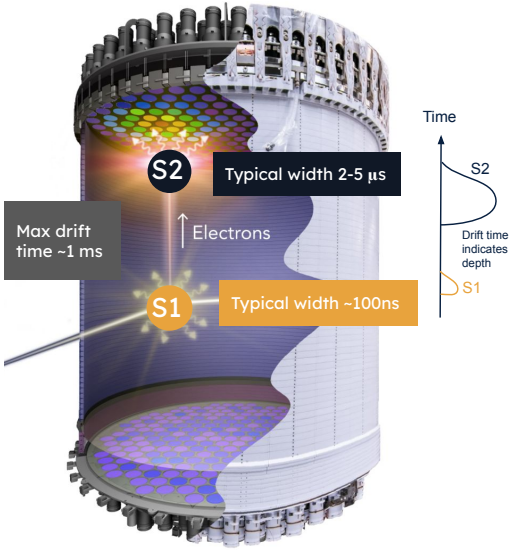
Sam Woodford

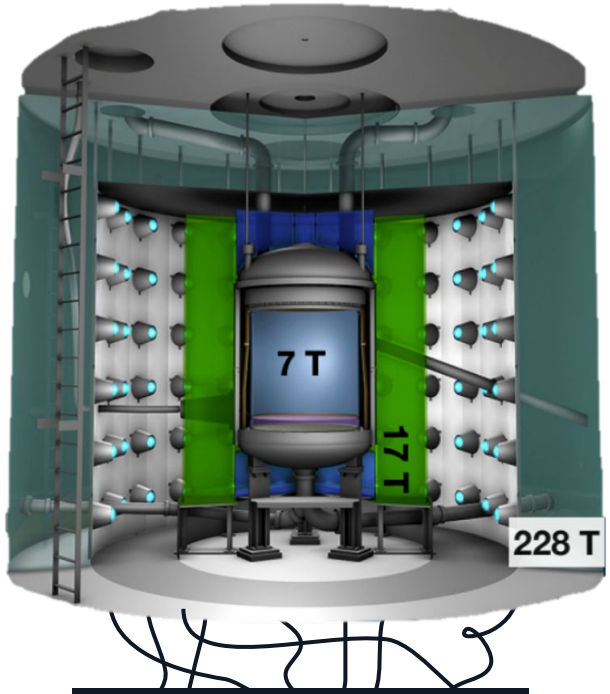


The LZ Detector

Xenon TPC

Dual-phase liquid xenon time projection chamber viewed by 494 PMTs:
253 on top, 241 on the bottom.

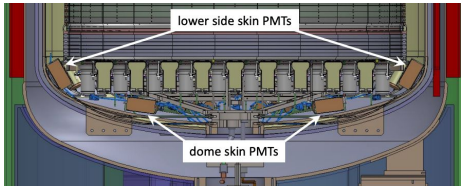




745 PMTs in total, all digitised by one system

Xenon Skin

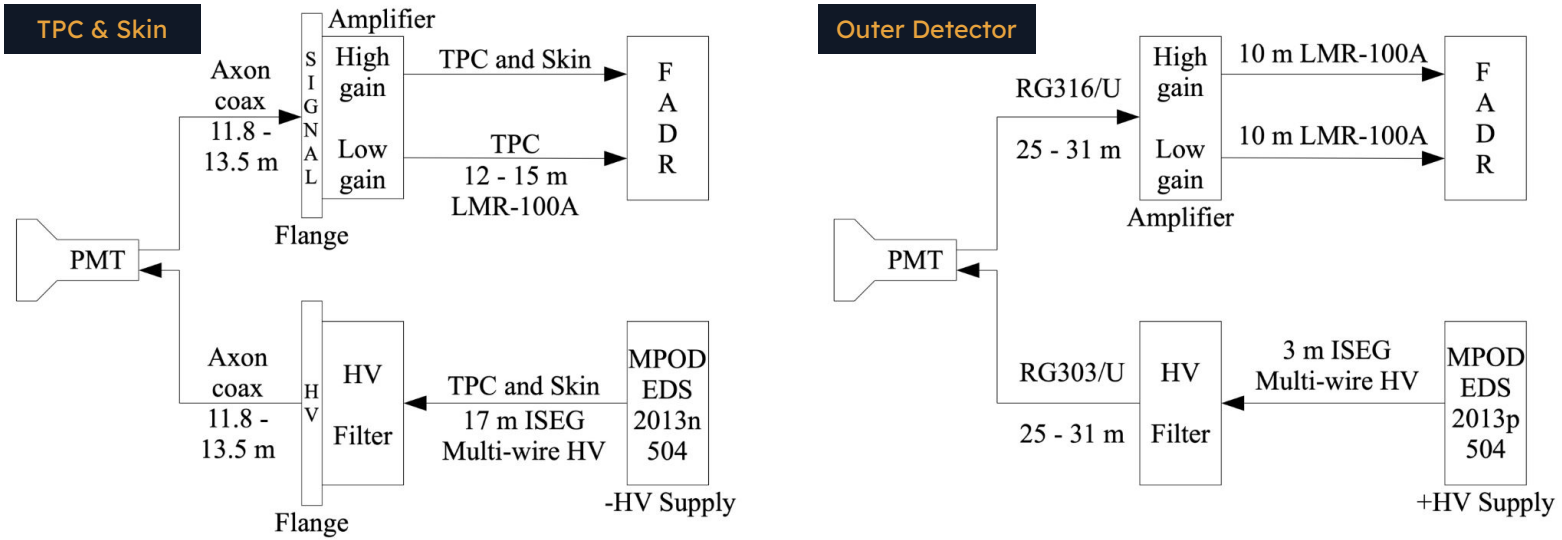
Xenon layer around the TPC, viewed by 131 PMTs. Tags gamma rays that coincide with TPC signals.



Outer Detector

120 8-inch PMTs in the water tank facing gadolinium-loaded scintillator tanks.
Tags neutrons.

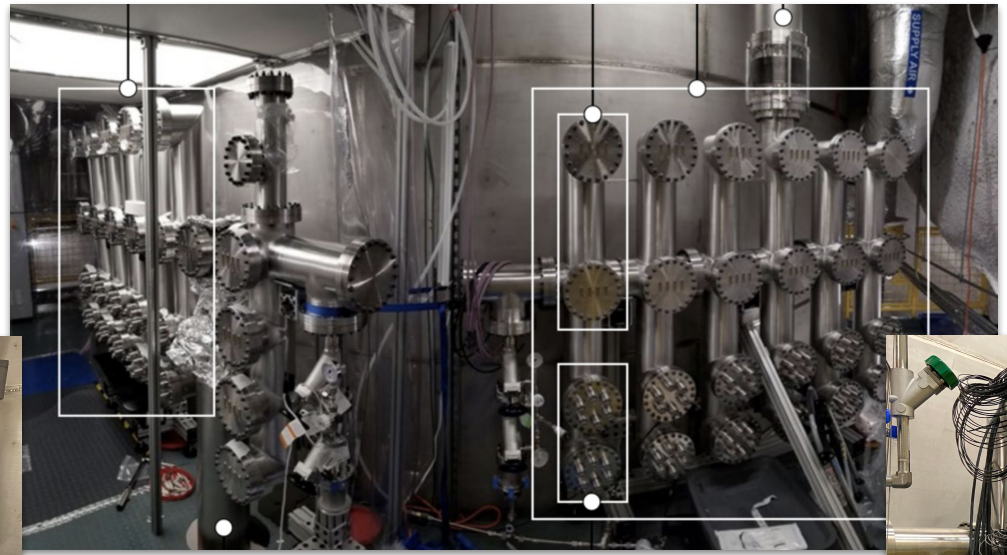
The Signal Chain



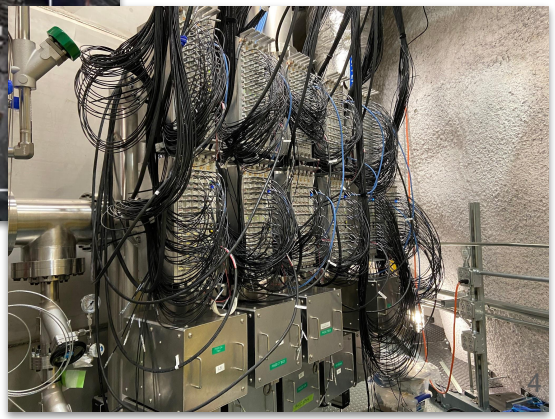
- PMT: Thin coax carries signals out of the cryostat to vacuum flanges with DB-25 feedthroughs. Flanges mounted on breakout boxes at side of the water tank
- Amplifiers: Dual-gain: high gain x 40 in pulse area (60 ns FWTM shaping), low gain x 4 in pulse area (30 ns FWTM)
- Cables: LMR coax runs the amplified signals to 3 electronic racks
- FADR: Digitises 1359 channels. Single photoelectron pulse ≈ 6 mV ≈ 50 ADCC (noise <4 ADCC)

The Signal Chain

Thin coax carries signals out of the cryostat to vacuum flanges with DB-25 feedthroughs. Flanges mounted on breakout boxes at side of the water tank

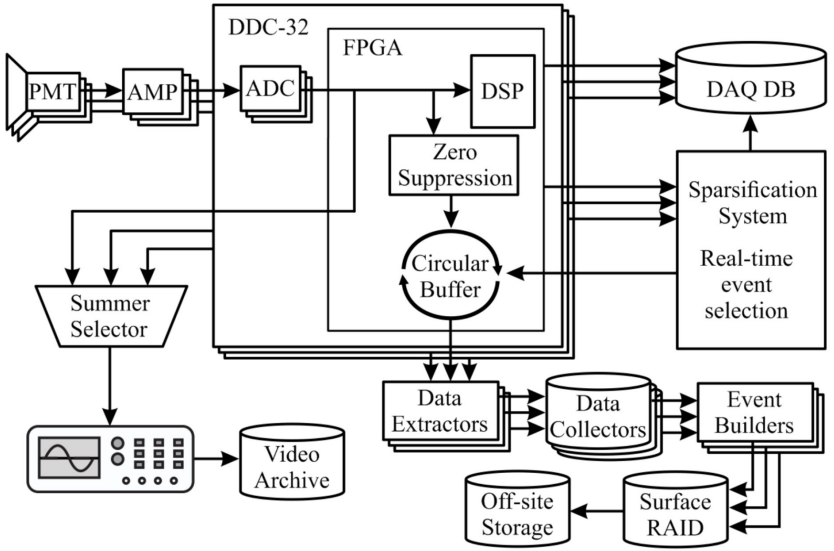






FADR

- FADR: FPGA-based Architecture for Data acquisition and Real-time monitoring. One system for making trigger decisions and acquiring and building events (uses the same digitised waveforms).
- DDC-32s: continuously digitise incoming PMT signals and store waveform data on circular buffers.
- When an event is detected, Data Extractors collect the data of interest from DDC-32s and send them to Data Collectors for temporary storage.
- Event Builders take the data, organised by channels, and assemble the buffers into full event structures for online and offline analysis.
- The system runs synchronously with one global clock.

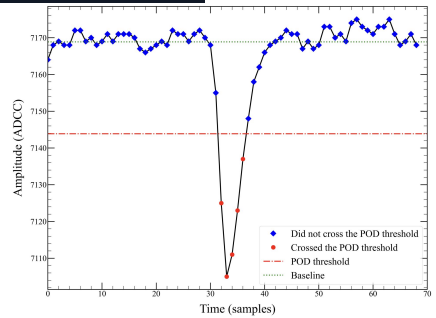


46 x DDC-32 Digitisers	16 x Data Collectors
6 x Data Sparsifiers	16 x Data Extractors
2 x Master Logic Boards	Max. data acquisition rate of ~1700 MB/s

Pulse-Only Digitisation

- In normal operation the DAQ operates in a zero-suppression mode, where only signals above baseline (32 sample rolling-average) are recorded in a given event window:

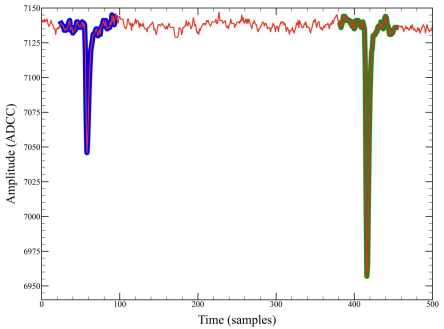
Zero-suppression



- A deviation of a sample from the baseline by more than the user-defined threshold, which is constant during a run, initiates the process that stores the waveform in memory.
- This process is called Pulse Only Digitisation and the stored waveform is called a POD.
- If another threshold crossing occurs during the post-sample period, the overlapping PODs are merged.

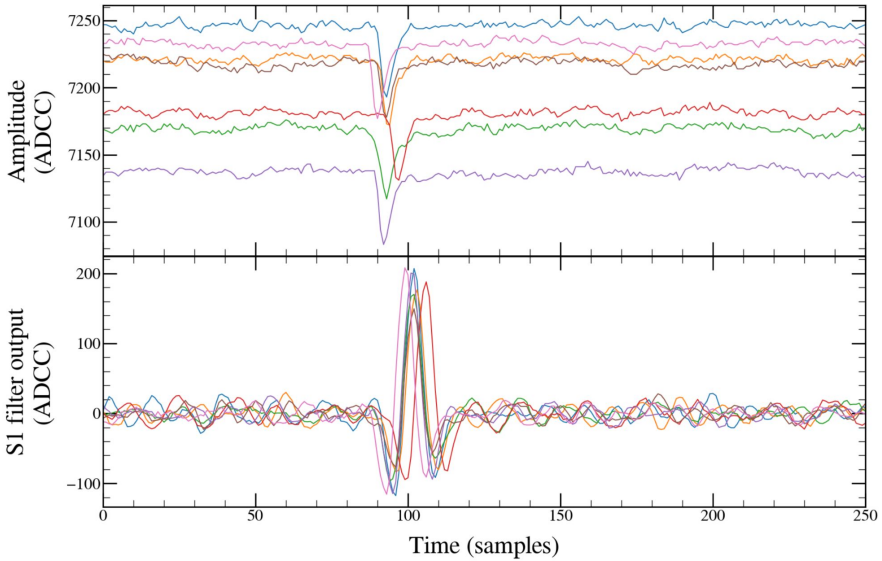
Non-zero-suppression

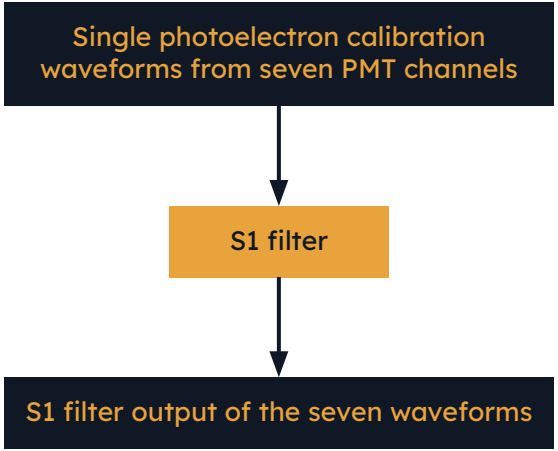
- We have developed and used the ability to acquire waveforms in zero-suppressed and non-zero-suppressed mode in parallel:
  - In this parallel mode we can acquire data from 16 physical channels on each 32-channel digitizer at a time.
  - This allows us to perform bit-level off-line consistency and performance checks of the zero-suppression algorithms.



Filters

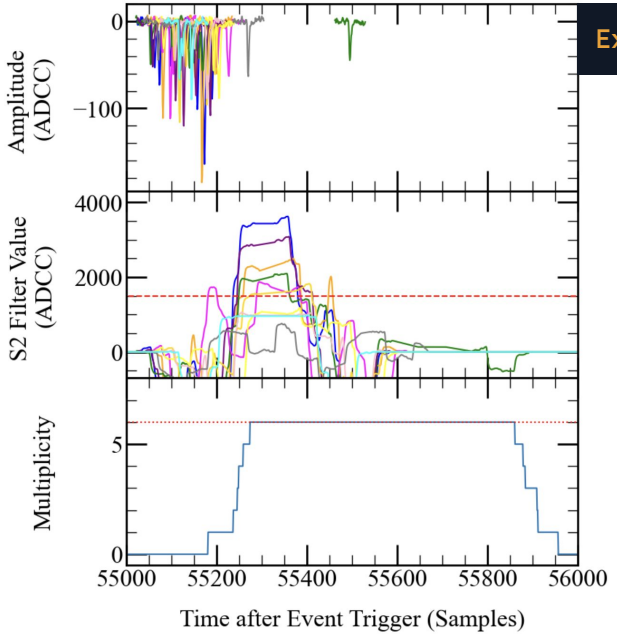
- Primary event selection is based on our FPGA digital filters that continuously process, in parallel, each PMT channel.
- In order to reduce sensitivity to baseline variations, waveforms are processed by Finite-Impulse-Response (FIR) filters.
- The filters provide **baseline subtraction** and a response proportional to the **pulse area**.





Data Sparsification

- S1 and S2 filters are continuously applied to the waveforms and information about which PMTs are above the filter threshold is communicated to the Data Sparsifiers
- Each time a PMT has a filter output that is above threshold, it will contribute to the total multiplicity for the next C samples, where C is the width of the coincidence window in samples



Example of S2 pulse with 190 photons detected across 50 PMTs

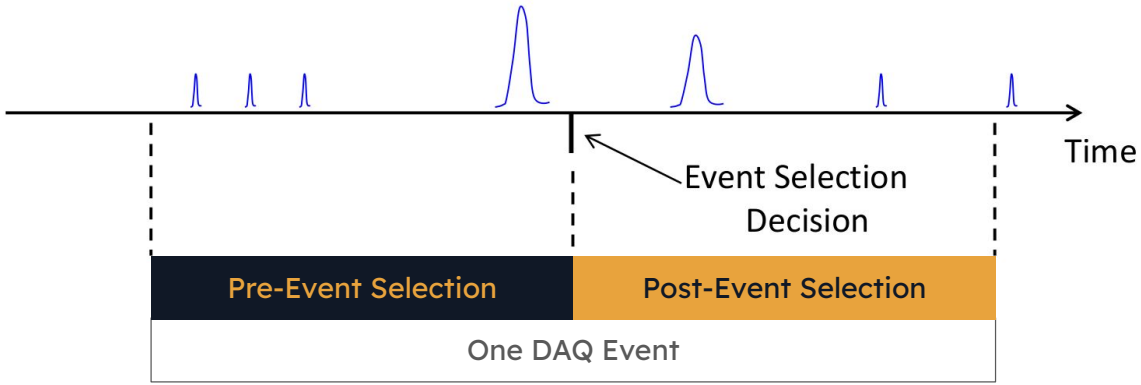
- Top: baseline-subtracted waveforms of the 50 PMTs
- Middle: S2 filter values for the ten brightest PMTs of the event. Red dashed line is the S2 filter threshold in ADCC
- Bottom: multiplicity array that is used to make the event selection. Red dashed line is the multiplicity condition for the S2 trigger

Event selection parameters for LZ's first Science Run:

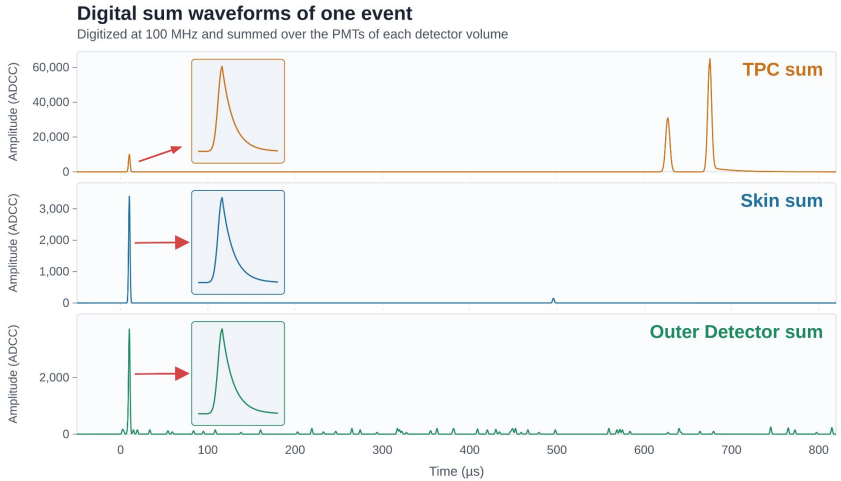
System/ Filter	Filter Width (samples)	Threshold (ADCC)	Coincidence Width (samples)	Multiplicity
TPC/S2	244	1500	500	6
OD/S1	15	3000	32	15

Event Selection

- The decision to preserve the current event is sent to the Data Acquisition Master
- The time range of the waveform data extracted from the DDC-32 digitisers is defined by the pre-event window and the post-event window. The lengths of the pre-event and post-event window times are configurable parameters that can be adjusted for each acquisition.
- During WIMP Search acquisitions, the pre-event window is 2 ms, and the post-event window is 2.5 ms:



Event Selection



- Much of the information about a given selected event (e.g. individual PMT channel IDs) is stored alongside the waveform data.
- Allows offline cross-checking and verification of the system's performance.
- When an event is selected for readout, the waveforms from all PMT channels are included in the event, independently of which detector volume generated the trigger.

Two major waveform-selection modes:

- Signals in the Skin and OD are S1-like signals. The Skin and OD use the S1 mode to trigger on these detector volumes.
- In order to be sensitive to S2-only events in the TPC, the TPC trigger uses the S2 trigger mode.

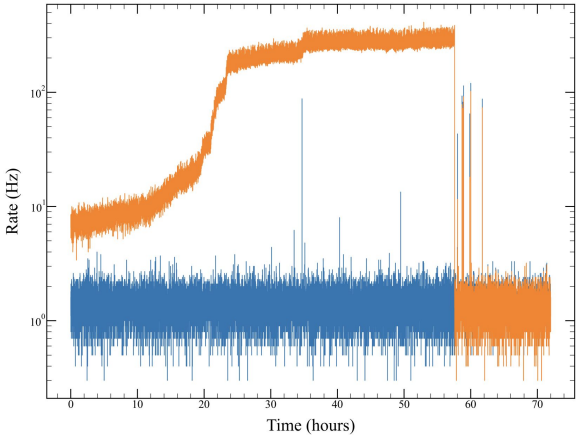
Trigger Mode	Description
S1 mode	Detection of coincident S1-like signals across selected channels. No fiducialization.
S2 mode	Detection of coincident S2-like signals across selected channels. Fiducialization in the x,y plane is possible for the TPC PMTs.

Rate & Noise Monitoring

The FPGA on each DDC-32 continuously monitors various rates that are important to ensure the proper operation of the detector and the electronics. These rates are sensitive to electronic noise, light emission in the detector, and/or the various trigger rates.

The following rates are captured every 10 s:

- S1 filter threshold crossing rates for each PMT channel. Two different S1 filter parameters are used for each PMT channel: one set of parameters are chosen to make the filter rates sensitive to electronics noise, the other set of filter parameters is selected to monitor the SPhE rates in the PMTs. These S1 filters operate in parallel to the S1 filters that are used for event selection.
- S2 filter threshold crossing rates for each PMT channel. Similar to above.
- POD threshold crossing rates for each PMT channel.
- The number of samples above the POD threshold per second for each PMT channel.
- The individual trigger rates for all detector systems, including the external triggers.



Example of a grounding problem developed with one of the amplifiers. This caused the noise rate in the channels associated with this amplifier to increase significantly.

Triggers

WIMP Search Triggers

In WIMP searches, detector based event selection is the logical **OR** of the following:

TPC S2 Trigger:
This trigger is based on an analysis of the S2 filter response of the high-gain signals of the top TPC PMTs.

Skin S1 Trigger:
This trigger is based on an analysis of the S1 filter response of the high-gain signals of the Skin PMTs.

OD S1 Trigger:
This trigger is based on the S1 filter response of the high-gain signals of the OD PMTs.

External triggers for monitoring background, detector health and FADR:

Random Trigger:
This trigger operates with a random rate of around 4 Hz and provides an unbiased sample, allowing us to monitor the background in the detector and the efficiency of the S1 and S2 triggers.

GPS Trigger:
This trigger runs at exactly 1 Hz, independent of detector signals, to monitor detector health. This trigger also allows us to measure the live time of FADR online and offline.

Calibration Triggers

External triggers are used primarily during certain calibrations (logical **OR**):

DD Triggers:
This trigger is generated by the pulsed neutron generator.

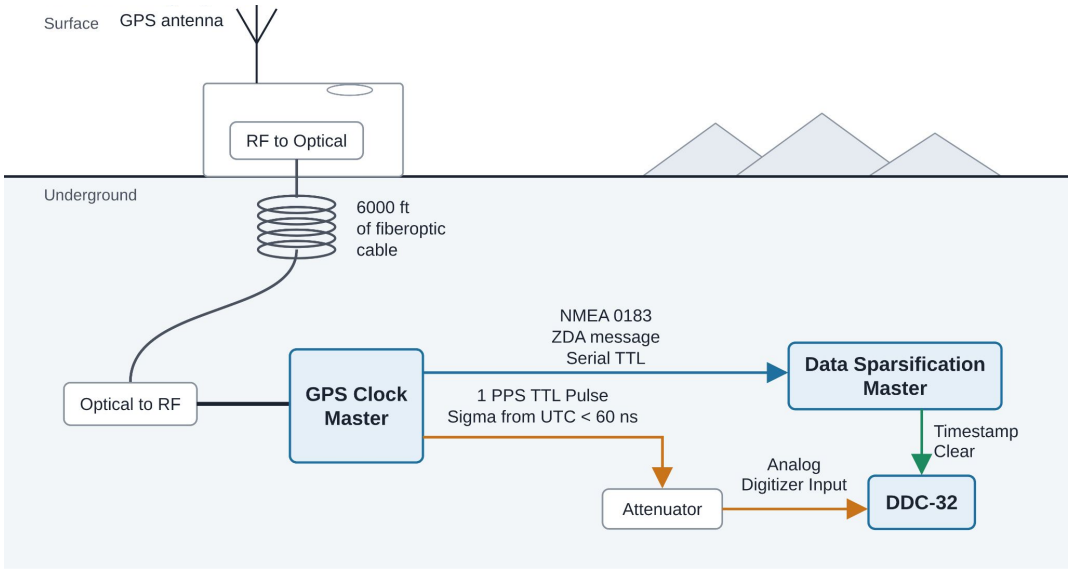
LED Triggers:
Multiple LED systems are used to calibrate and monitor the health of the PMTs. Each of these systems generates a trigger signal when the LEDs are fired.

Calibration Source	System	Count Rate (Hz)	Event Size (MB)
^{83m}Kr	TPC	<150	0.8
^{22}Na	TPC/Skin/OD	10	0.9
^{57}Co	Skin	135	0.2
DD neutrons	TPC	<150	2.1
AmLi neutrons	TPC/OD	55	3.0
LEDs	TPC/Skin/OD	1,000	0.06

For comparison, typical rate during WIMP search is 15 Hz, with an event size of 0.9 MB

GPS Timestamping

Timing system schematic



1. A GPS antenna is mounted on the roof of the administration building at SURF. Optical Zonu GPS-over-Fiber extenders are used to get the GPS signal to the underground master clock.
2. A Trimble Mini-T GG Multi-GNSS Disciplined Clock is used as our GPS master clock. It is designed to provide the 1 pulse-per-second (PPS) signal with a 15 ns (1-sigma) accuracy.
3. When an acquisition is started, the Data Sparsifier Master resets FADR's internal 48-bit timestamping counter to zero and aligns it with the rising edge of the PPS pulse coming from the GPS master clock.
4. An attenuated copy of the 1 PPS pulse is digitized by one of the DDC-32 channels along with the PMT signals.

Livetime

Buffer times

Each channel of the DDC-32 has two circular buffers. Data can be written to one buffer while data from the other buffer is being transferred.

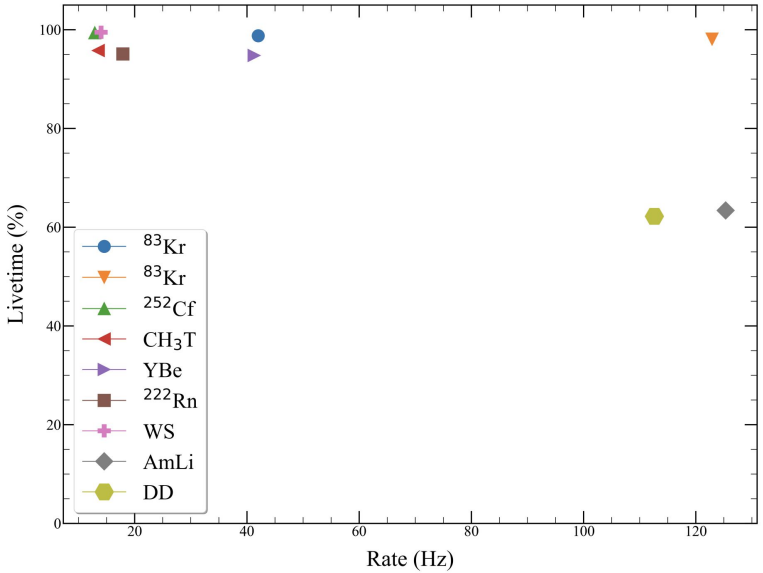
For each buffer, the start and end times are captured in the data stream. The buffer start time is the time that a buffer is ready to receive data; the buffer end time is the time of the end of the event or when the first buffer of a particular digitiser is filled.

Livetime

If the buffer stop time of event n is larger than the buffer start time of event n + 1 there is no deadtime associated with switching buffers.

If the buffer stop time of event n is less than the buffer start time of event n + 1 there is period when no data could be captured and deadtime is incurred.

This happens when one buffer is transferring data and the second buffer is waiting to transfer data.



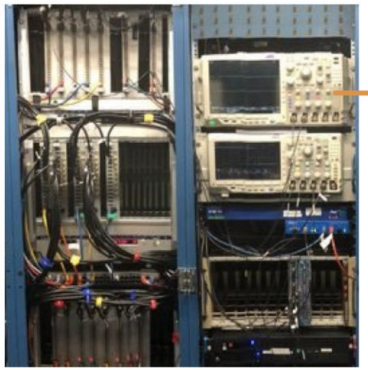
Raw DAQ livetime (fraction of time the DAQ is able to accept triggers). Livetime is a function of event rate and event size. E.g. for neutron sources, the event is three times larger than event size in a WIMP Search.

Backup

Real-time non-intrusive signal probing

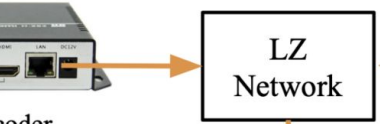
The DAQ system allows an operator to look at any one or sum of selected PMT signal channels on a Tektronix scope with remote controls and video streaming.

- Multiplexing and summing is done digitally, thus there is no need to unplug or replug physical connections.
- This is done at full 100 MHz sample rate with no zero-suppression.



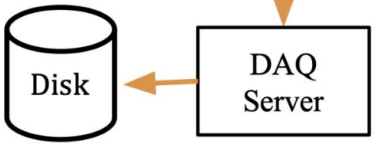


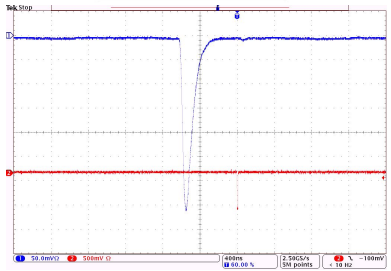
Video to IP Encoder







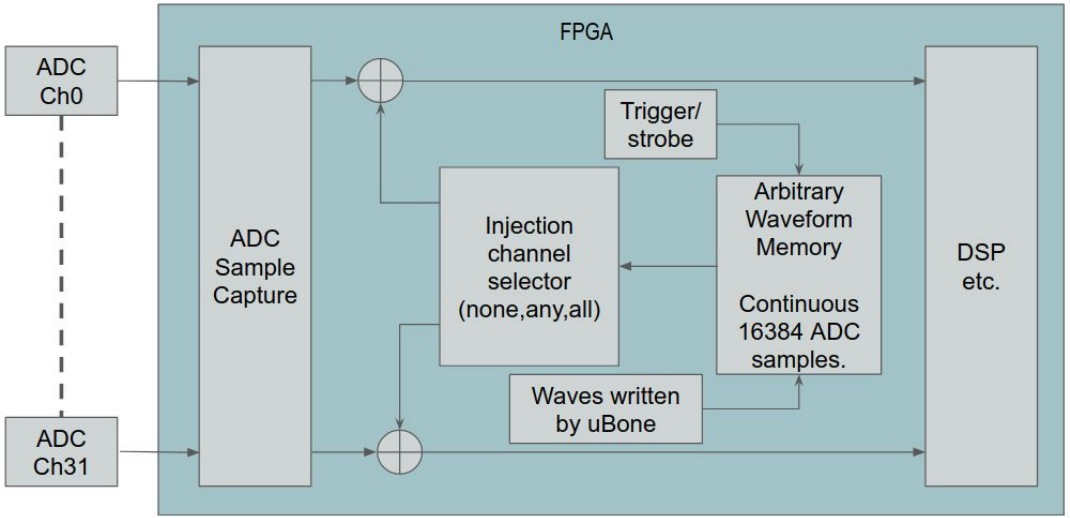




Arbitrary waveform injection

We have the capability of loading arbitrary waveforms into the DDC-32s and injecting them.

- As if they came in on the cables plugged into the digitizers.



- We have used this functionality to develop and extensively test:
  - The zero-suppression algorithm
  - Data sparsification