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Acknowledgments

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I was priveledged to spend nearly a year and a half of my Ph.D. out at Fermi National Accelerator Laboratory, near Chicago, IL, USA, and found it an incredible place to live and work. I'm not exagerating when I say during my time there I would have happily never left! I am incredibly grateful to Dr. Michelle Stancari, Dr. Tom Junk and Dr. Tingjun Yang for giving me all the opportunities and being some of the most fun and productive people to work with – I consider myself extremely lucky to have had the opportunity to work closely with you all. I hugely enjoyed being a part of the 35-ton operations team and so must also thank Dr. Alan Hahn for his endless knowledge and conversation.

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Special thanks must be extended to my parents, and my brother, for their love and support throughout my entire life. I would never have got to the stage where I'm writing this mammoth document without the opportunities you have afforded to me, so I hope this thesis goes some way towards showing this gratitude!

Finally, last but certainly not least, to my amazing wife, Jenny. How you have put up with me, and all the physics, over the last eight years is beyond me but I'm constantly amazed by the level of love and support you show, and have shown right the way through my undergrad and Ph.D. Thanks for your continued patience throughout the years as we've been apart during my time in Warwick, Sheffield and Chicago. I wouldn't be where I am now without you and words cannot describe how much you have done for me (but if they could, they'd probably be in the form of this thesis!).

Proposed chapters:

Introduction

- Intoduction to neutrino physics
- Current understanding
- State of neutrino physics field
- Motivation for further research and future experiments!

Neutrino Physics

- Relevant theory
- Current experiments
- Future experiments
- Description of the liquid argon TPC concept

DUNE

- Description of the DUNE experiment
- Motivate 35t

The 35t Prototype Experiment

- Everything! Long chapter
- Materials Test Stand
- LAPD
- 35t - Cryostat
- 35t - Detector
- 35t - Detector Electronics/DAQ
- Sheffield camera system

Online Monitoring for the 35t

- Online Monitoring

- Event Displays

Reconstruction in LArTPCs

- Full reconstruction chain
- Detailed discussion of the developed reconstruction techniques

Detection of Pi0s in 35t

- Some kind of analysis!
- Who knows, really?...

Electron Reconstruction for ν_e Oscillation Signal at the DUNE Far Detector

- Short extension of the reconstruction work to the DUNE far detector.
- Discuss importance of finding electrons in the FD (oscillation signal!)
- Show we can reconstruct ν_e FD electrons; reconstruction efficiencies/completeness/cleanliness etc.
- Separation of electrons and photons
- Show separation between pi0 and electron; this would be a result!

Summary

- Summary

Chapter 1

Introduction

Chapter 2

Neutrino Physics

Neutrino physics will be discussed!

– Theory

– Experiments

– Future Experiments

It may make sense to discuss the experiments as we go along...

I think the chapter will work best with both past, present and future woven together.
And no distinct separation between theory and experiment (this is an experimental thesis after all...).
Can discuss the 'neutrino problems' to motivate the theory of neutrino oscillations, and include the SNO and Kamiokande results within.
Then something similar with mass.
And as we get onto unanswered questions, can weave the propsed experiments into this.
I feel a section on the technology and concept of LAr TPCs will fit nicely into this setup.

2.1 Neutrino Theory

2.1.1 Neutrino Oscillations

Derive 2-flavour case.

Extend to 3 flavour.

Discuss CP violation.

2.1.2 Neutrino Mass

Mass hierarchy.

Absolute mass.

2.2 Future Neutrino Experiments

2.3 The LAr TPC Concept

The use of a liquid argon time projection chamber (LArTPC) as a high-precision fine-grained detector medium holds much promise for the successful resolution of the open questions in neutrino physics. A great amount of R&D work has taken place to advance the maturity of the technology and pioneering experiments, such as ICARUS [1], have further increased the understanding of the neutrino community of the detector techniques. Past and currently running experiments at Fermilab, such as ArgoNeuT [], LArIAT [] and MicroBooNE [], are successfully using LArTPCs to take and analyse data and it seems certain to be the future of neutrino physics in the U.S.

This section will provide a brief history of LArTPC technology and motivate its potential when used in a huge experiment such as DUNE. The basic operation of such a detector will also be described to provide background for discussion of the DUNE and 35t experiments, and of reconstruction in LArTPCs, in future chapters.

2.3.1 A Brief History of Time (Projection Chambers)

The use of a time projection chamber as a potential particle detector was put forward by David Nygren in 1974 [5]. He envisioned bubble-chamber quality data but with the possiblity of digital readout of the data, fascilitating extremely fine spatial resolution, good timing resolution and fast recovery after triggering. The basic concept is a drift chamber containing a noble gas placed within a field to drift ionisation electrons created by a propagating particle towards a multielectron array. This setup allows full three-dimensional reconstruction by combining information from the two-dimensional readout plane with the drift time. Nygren also included a magnetic field to assist particle identification in his design, shown in Fig. 2.1.

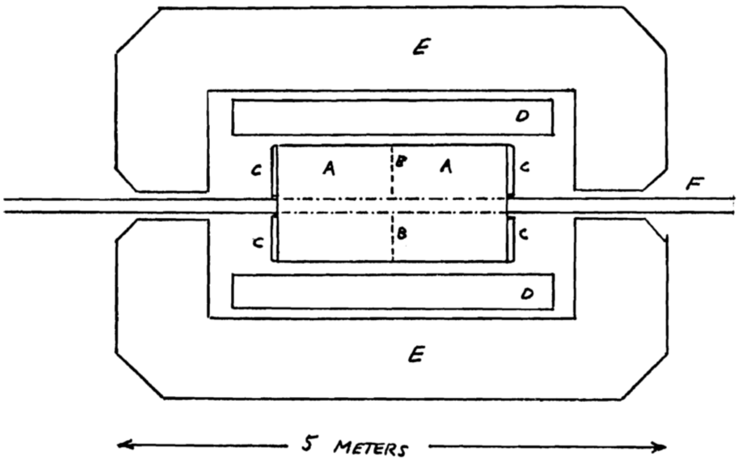


Figure 2.1: The original concept of the time projection chamber particle detector, drawn by David Nygren in 1974 [5].

The extension of this concept to a liquid argon TPC and it potential as a high-precision fine-grained detector medium in neutrino physics was proposed by Carlo Rubbia in 1977 [6]. The use of a noble liquid rather than gas is necessary in neutrino experiments to provide a high enough target mass to increase the probability of a neutrino interaction. Noble liquids have high electron mobility and low diffusion, favourable properties as the detection of particles is from the ionisation and scintillation light created by the particles. Given the necessity of a high electric field in order to drift these electrons to the readout places, excellent dielectric properties are also required; noble liquids possess such qualities. The properties of liquid argon which make it almost perfect for this use are demonstrated in the table in Table 2.1.

An additional advantage of this technology is the low threshold for detection; this is set by the ionisation threshold of liquid argon and is only 23.6 ± 0.5 eV []. Rubbia realised that a LArTPC could be the digital replacement for the high quality particle detection methods used in bubble chambers, very common in neutrino physics in the 1970s. He proposed the first LArTPC detector design, shown in Fig. 2.2, which bears a striking resemblense to the LArTPC used in experiments today.

Constructing and operating such a detector was beyond the technology of the time, and is still being understood today. The operation of a LArTPC detector and the challenges associated with this are the subject of section 2.3.2.

Table 2.1: Properties of noble elements relevant when considering a TPC medium for a neutrino experiment.

	Water	He	Ne	Ar	Kr	Xe
Boiling point [K] @ 1 atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ/MeV]	-	19 000	30 000	40 000	25 000	42 000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175
Natural abundance (Earth atm) [ppm]		5.2	18.2	9340.0	1.10	0.09
Electron mobility [cm^2/Vs]		low	low	400	1200	2200

2.3.2 LAr TPC Operation

explain how they work

new subsubsection

[FIND OR MAKE A FIGURE TO GO WITH THE FOLLOWING DESCRIPTION...]

A LArTPC typically consists of a single, or multiple anode and cathode, at either end of an active drift region. An ionising particle passing through a LArTPC causes electrons to become free from argon atoms and, in the presence of a field, drift towards an anode where they are read out.

The readout consists of multiple wires planes with different orientations to facilitate the reconstruction. The wires are either ‘induction’ wires, which allow the electrons to deposit charge but continue past, or ‘collection’ wires, on which the electric field lines end and all the charge on the electron is collected. Each wire plane is therefore held at a different ‘bias voltage’ to prevent any field lines ending on the induction wire, thus creating local electric fields which promote the continuing forward motion of the electrons. The signal seen is therefore dependent on the type of wire plane; a bipolar pulse on an induction plane wire and unipolar on a collection plane wire. It is also common, though not essential, to make use of a ‘grid plane’ upstream of the signal planes in order to shield them from the electron charge until they are close. Without such a plane, the bipolar pulse would be highly asymmetric, though would still have zero integral. It also makes changing the drift voltage (controlling the electric field) slightly easier

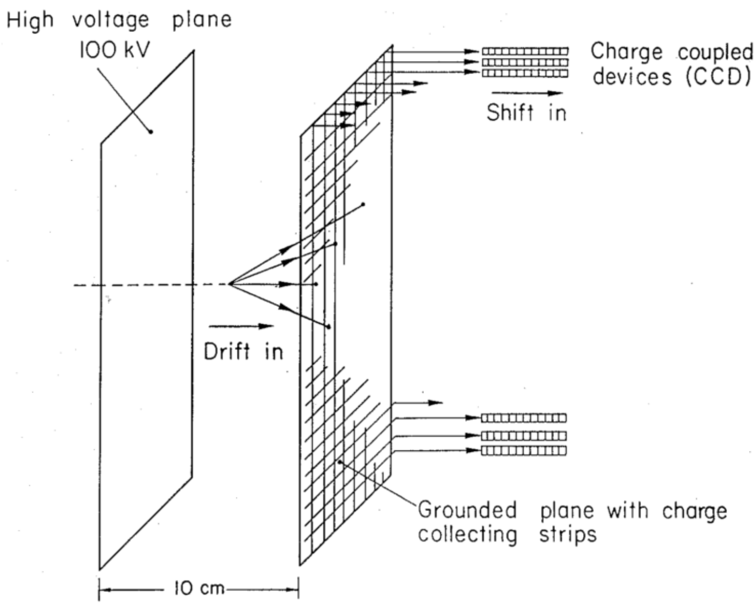


Figure 2.2: The LArTPC detector proposed by Carlo Rubbia in 1977 [6].

as the signal planes are somewhat shielded from its effects. MicroBooNE does not operate with a grid plane and, although the 35t and the DUNE reference design make use of a grid plane, it is uncertain whether the benefit outweighs the cost for a huge LArTPC detector such as the DUNE far detector. It is worth mentioning alternative readout possibilities have been suggested but, given the scale of future LArTPCs, it is highly unlikely a viable solution which delivers superior readout at a comparable cost will be found.

Given the positive ions that are left in the medium, there is the possibility of recombination at a later time and therefore a loss of information about the initial interaction.

This is however accompanied by a flash of scintillation light which is hugely useful as a means of determining the event 'start time' (t_0); without this information it would be impossible to place an absolute time scale on the interaction and we would therefore not be able to resolve the coordinate along the drift direction. The magnitude of the electric field applied is the key to both processes and there is thus a compromise which must be struck in order to preserve as much information as possible. The graph in Fig. **??** demonstrates this; a field of 500 V/cm is often chosen in current LAr neutrino experiments.

A cathode is held at a high voltage

Flesh this stuff out...

U plane, V plane and collection all held at different fields. Slightly increasing in order to promote forward motion of the electrons. V held at 0V because it's cheaper (don't need crazy voltages, just some negative (still quite high, 100V), 0V and some positive. Grid plane (also held at potential) is to sheild the APAs from the electrons until they are close. Not needed, but

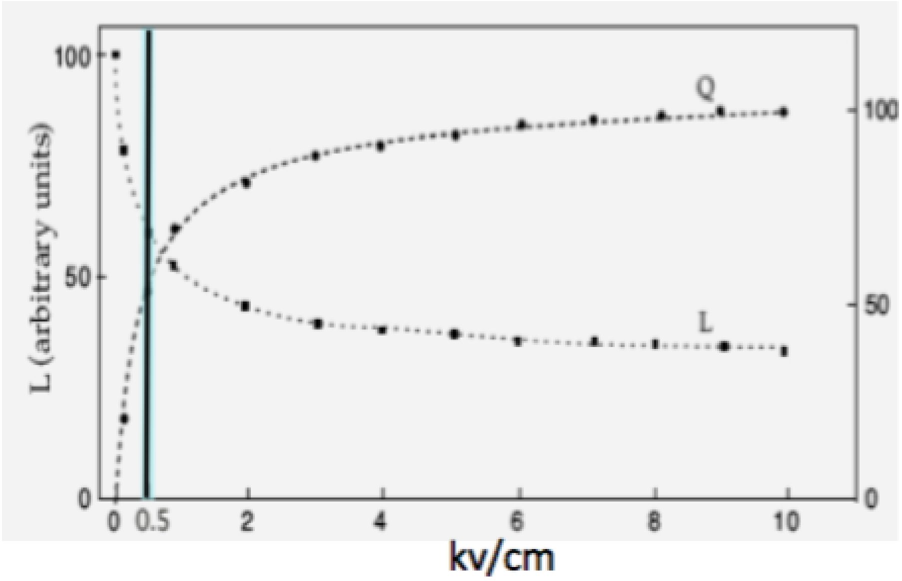


Figure 2.3: Demonstration of the competing effect the electric field has on the luminosity of the ionisation electrons and scintillation light arriving at the detector readout. Since both are essential in reconstructing the complete interactions, a balance must be found. [PLACEHOLDER IMAGE].

if not present then pulse wouldn't be very bipolar! The charge in both portions will still equate but the leading end will be muchhhh longer. All electric field lines (generated from movement of electrons) end on the cathode; don't want them to end on the induction wires (hence making sure the field increases). We want them to end on the collection planes, which collects the charge. Signal shaping time (along with gain, the two front-end ASIC parameters) is to let the charge leave the wire before being hit again (or something like this!). Deconvolution I still need to understand...

In 35t, we have FE ASICs which are the very front end and apply the signal shaping and gain. Have regulators to control the power these receive (these are noisy...). Also ADC ASICs to do digitisation in the cold. MicroBooNE don't do this, this just have the front end and do everything else in the warm. FE ASICs are the problem, same for uBooNE and 35t. ADC ASIC has stuck code problem.

Chapter 3

The DUNE Experiment

Chapter 4

The DUNE 35t Prototype

The 35t is a prototype experiment for the DUNE far detector design. It was contructed to prototype the unique design features of the LBNE far detector and was the only planned prototype for this detector. Following the dissolution of LBNE and the subsequent merging along with LBNO into the DUNE experiment, the 35t has become an integral part of the design and execution of the DUNE far detector design.

The 35t consists of a membrane cryostat (Sec. 4.3), designed to be filled with 35 metric tons of liquid argon, and a small-scale DUNE-style detector (Sec. 4.4) including a TPC and photon detectors. It was constructed in 2012 at PC4, a former proton facility in a decomissioned beamline, at Fermilab. The Phase I run, without a detector, took place between December 2013 and February 2014. Between February 2014 and September 2015 the detector was constructed and heavily tested at FNAL before being installed inside the cryostat ready for the Phase II run. This took place between February 2016 and April 2016 (offically starting on 11th February, as I type!).

4.1 Motivation

The use of liquid argon TPCs (LArTPCs) for the study of neutrinos in long-baseline experiments shows great promise and is the direction neutrino research, particularly in the US, is headed. Fermilab has an extensive program of LArTPC experiments to design, test and improve such detectors, culminating in DUNE, the flagship experiment due to come online in the early 2020s. Although they exhibit great physics potential, they do not come without significant engineering challenges. For example, DUNE will have four 10 kton cryostats containing liquid argon kept at very high purity. Constructing such a cryostat is itself difficult and expensive but in order to achieve, and maintain, the required purity, much R&D is required.

Previous LArTPC experiments, such as ICARUS [], Argoneut [], LArIAT [] and MicroBooNE [] (?), have been contructed as flat plane vessels and have used an evacuation method as the first step in removing atmospheric impurities which would contaminate the liquid argon. Constructing the DUNE far detector cryostats in a similar mannor would be both very expensive and incredibly challenging. In order to investigate possible alternatives, the Fermilab program includes the Liquid Argon Purity Demonstrator (LAPD) and 35t experiments, together showing a cheaper and more feasible approach to designing and operating LArTPCs. These experiments are the subject of the present chaptor.

4.2 The Liquid Argon Purity Demonstrator

The Liquid Argon Purity Demonstrator (LAPD) [7] was designed to demonstrate that the required purity of future LArTPC experiments is possible to acheive without the use of large scale vacuum pumps. The required mechanical capability of the cryostat to withstand such a method, along with the operation of the evacuation system itself, adds a considerable amount to the cost of the project. Suggestions to get around this include using multiple smaller scale cryostats, but this leads to greater complexity relating to both the engineering requirements of the piping infrastructure and the reconstruction capabilities of interactions spanning numerous fiducial volumes. LAPD successfully pioneered the method of using purging as the first step in purification of the liquid argon. This important result is discussed below and has significantly influenced the design of future LAr cryostats, including the 35t.

4.2.1 LAPD Experimental Setup

LAPD consists of a cylindrical tank (diameter 10 feet, height 10 feet) with a domed head capable of holding 32.6 tons of liquid argon. It is instrumented with cryogenic equipment and a purification system, consisting of two purifiers and a piping system. Figure **??** shows a CAD model of the tank and purification piping.

Insulation for the tank is provided by fibreglass sheets covering the outer volume which, along with the tank, is refrigerated by liquid nitrogen from an external supply. There also exist cooling coils near the top of the tank which serve to recondense vapourised argon and feed it back into the tank, via the filtration system.

The liquid argon is fed into the tank from outside PC4 The argon purity is maintained through the use of the purifiers, located outside of the main volume. Argon is constantly

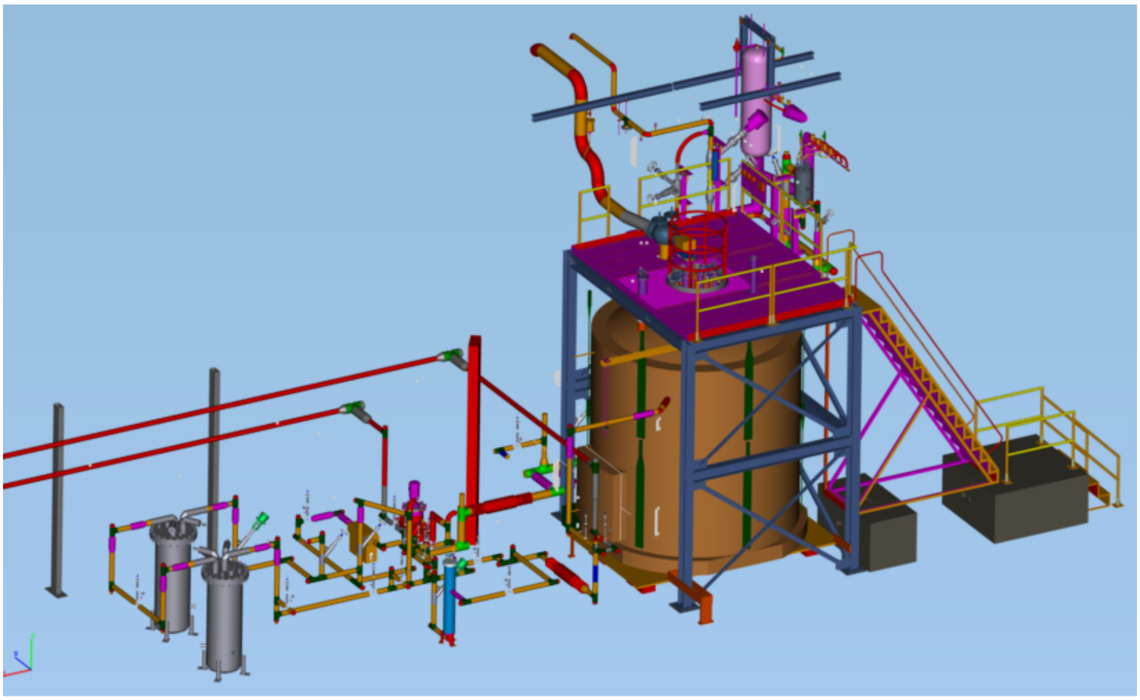


Figure 4.1: The LAPD tank and purification system [7]. The domed tank on the right, beneath the platform, is the cryostat. The piping allow the flow of liquid argon into and out of the cryostat and is used as part of the purification system. Two cylindrical purifiers, visible in the lower left of the figure, remove contaminants from the argon as it is pumped through. All components of the experiment are discussed in the text.

circulated from the tank to these vessels through stainless steel pipes. The filtration system used by LAPD, and subsequently by the 35t cryostat, is discussed in greater detail in ection 4.2.2.

4.2.2 The LAPD Filtration System

A LArTPC relies on the detection of the drift electrons produced upon ionisation of the argon by a propagating particle. Electronegative contaminants in the medium jeopardise this process by recombining with the electrons before they can reach the readout electronics. The phase 'electron lifetime' therefore refers to the amount of time that an electron will typically drift along the electron field, and is directly related to the concentration of impurities in the liquid. Even using a modularised detector, as the DUNE far detector will be, drift lengths on the order of 5 m are realistically required, leading to purity requirements of several milliseconds. The dominant contaminents which are removed by the LAPD and 35t filtration system are oxygen and water.

The liquid argon is extracted from near the bottom of the tank and returned to the top after passing through the purifiers. It first passes through the water filter before continuing on through the oxygen filter. The water filter comprises a molecular sieve which prevents the propagation of large molecules, such as water. This purification step must occur first since the proceeding filter also removes water molecules and would therefore be less efficient at removing oxygen if used first. The oxygen filter consists of a thin activated-copper layer on an alumnia substrate [2]. Both filters will lose some functionality over time as they collect more and more impurities and so require 'regenerating' in order to remove the contaminants. This can be done in-situ, as described in [2]; this complicates the design of the filter but is necessary when considering the purification system required for the full DUNE far detector.

The contamination gradient, and associated purities at each stage during the LAPD Phase II run, is shown in figure 4.2. These purities are known through the use of purity monitors; these are the subject of section 4.2.3.

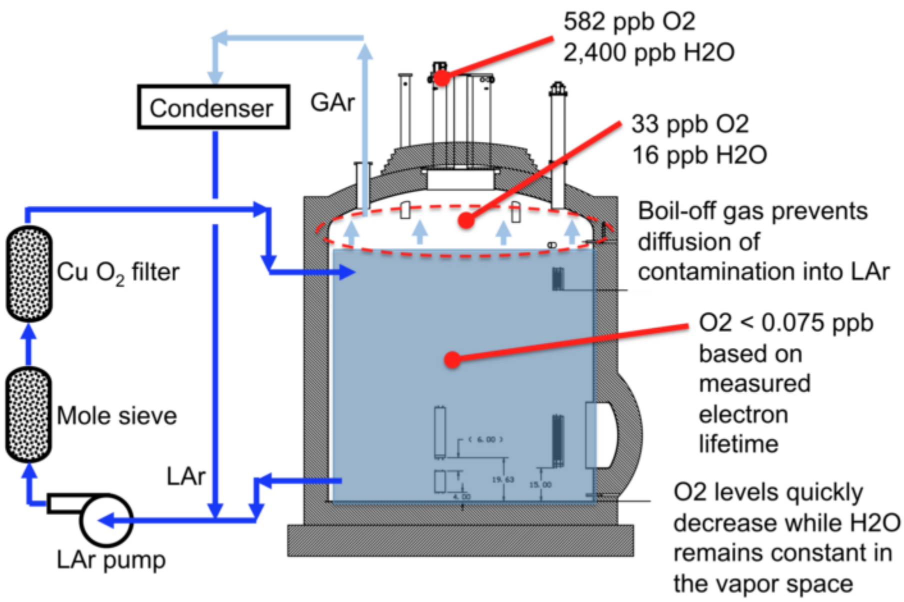


Figure 4.2: Contaminant gradient in the LAPD tank at different stages of the purification process [7]. The associated LAr purities, in units of parts-per-billion (ppb) are also shown.

4.2.3 Purity Monitoring

As discussed in section 4.2.2, extreme LAr purity is required for the successful readout of ionisation electrons by the electronics. These purites must be constatly monitored to ensure the high quality of argon necessary during data taking. Since these impurity concentrations on beyond the capabilities of many conventional gas analysers, a device called a purity monitor is employed. Such a device is shown schematically in figure 4.3.

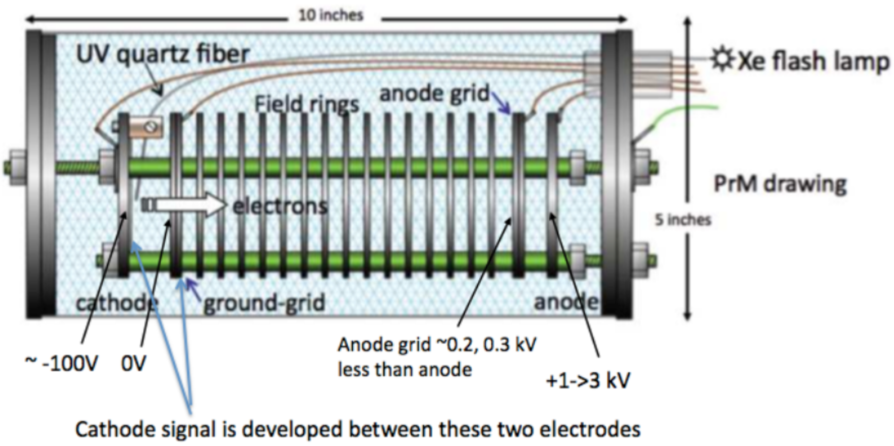


Figure 4.3: Diagram showing schematically the design of purity monitoring used in LAPD, and subsequently the 35t experiment [3]. Their use is described in the text.

The purity monitors deployed consist of a cylindrical volume, filled with LAr for its surrounding environment. They contain a photo cathode and an anode, between which lies short drift volume. When taking purity measurments, light from a Xenon flash lamp is incident on the cathode, liberating photoelectrons which traverse towards the anode. Electronegative impurities in the LAr will decrease the electron lifetime and therefore the mean number of electrons reaching a certain point along the drift volume. A measurement of the ratio of the charge arriving at the anode to that at the cathode is hence a measurement of the inherit purity of the liquid.

These monitors were placed both in the LAPD tank and just after the filtration system in order to study the purity at different points in the recirculation. Several gas analysers, measuring nitrogen, oxygen and water contaminants to various levels of accuracy, were also used. Temperature sensors to measure the vertical temperature profile within the cryostat were necessary to account its effect on the electron drift velocity.

Several of the technologies pioneered in LAPD were also used in the 35t experiment, as will be shortly discussed.

4.2.4 LAPD Results

LAPD successfully demonstrated achieving and maintaining the required LAr purity for a large neutrino detector is possible without the costly and challenging use of evacuation techniques. It initially ran for six weeks and reached a purity of better than 60 ppt (parts-per-trillion) oxygen equivalent [7]. The measured electron lifetimes over the course of the run is shown in figure **??**. As can be seen, electron lifetimes of up to 4 ms were reached, which is [put into context with current DUNE requirements!].

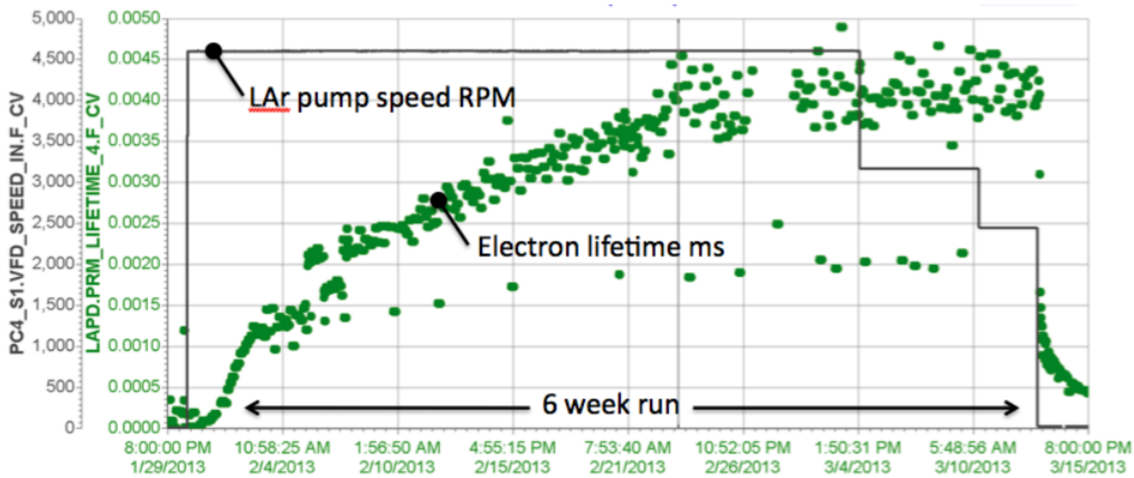


Figure 4.4

This important result has great significance when considering future LArTPC experiments and laid the way for the 35t experiment. This experiment will now be discussed in the subsequent sections.

4.3 The 35t Cryostat

The 35t prototype takes advantage of membrane cryostat technology and is the first test of this construction technique for LArTPCs. Membrane cryostats have been widely used in the liquified natural gas industry for many years but the 35t experiment is the first to make use of the technology for liquid argon. Furthermore, it is the first membrane cryostat to be constructed in the United States and the first to be constructed for scientific purposes [4]. The 35t cryostat is the subject of the present section.

4.3.1 Construction

Boring stuff about cement and shit.

Cryostat!

4.3.2 The 35t and LAPD

It's near LAPD!

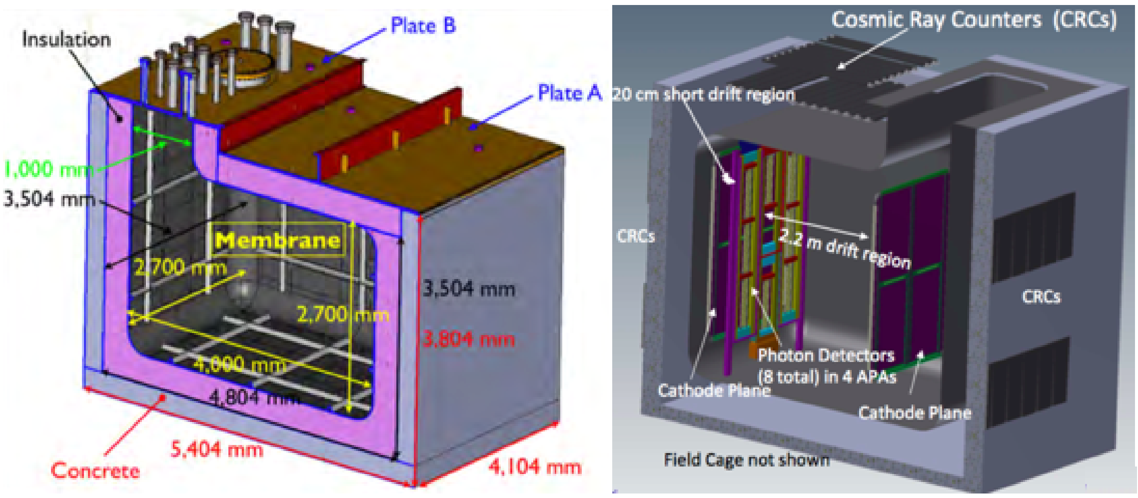


Figure 4.5: The 35t cryostat [3]. The cryostat as operated during Phase I is shown on the left and the corresponding version, including a full small-scale detector, used in Phase II is on the right.

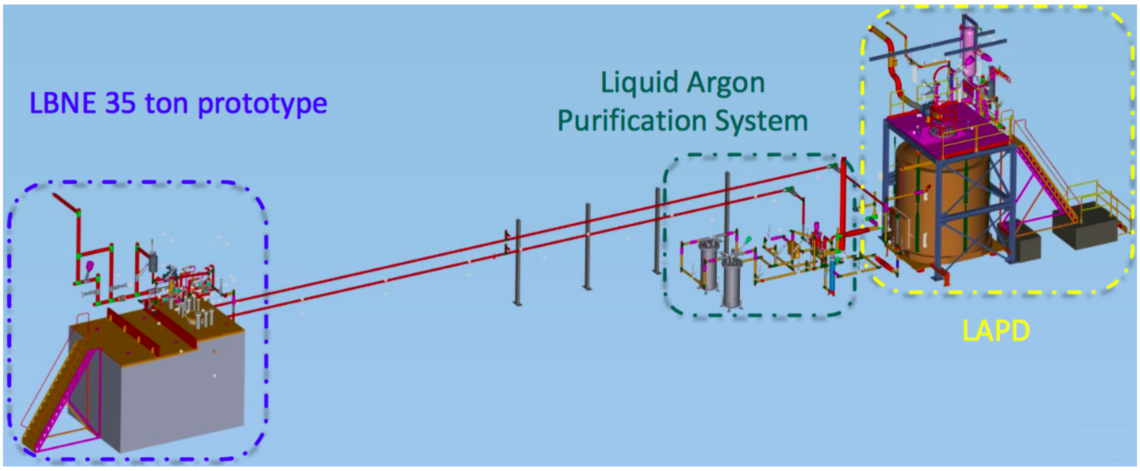


Figure 4.6: [3].

4.4 The 35t Detector

4.4.1 Detector Components

TPC

Photon Detectors

External Counters

4.4.2 Readout Electronics

FEMBs

RCEs

SSPs

PTB

4.6.2 Purity Monitoring

Same as LAPD.

4.7 35t Phase I

4.7.1 Outcomes

4.8 35t Phase II

4.8.1 Commissioning

4.8.2 The Sheffield Camera System

Wait for Nicola to finish the paper and plagerise!

4.8.3 Online Monitoring for Data Quality Monitoring

4.8.4 Outcomes

Chapter 5

Online Monitoring & Event Displays for the 35ton

Monitoring of the data collected during the running of an experiment is imperative to ensure a high quality of data is maintained. Such monitoring is often provided in real-time ('Online Monitoring'), summarising the data from the current run, or in near real-time ('Nearline Monitoring'), summarising data over runs from typically the previous day, week or month to represent the longer term fluctuations in the data quality. The system developed to provide online feedback for the 35ton Run II data taking period is discussed in this present section.

An event display, designed to illustrate physics events as they occur in the detector, is another desirable feature hugely useful during data collection. A basic example of such a display is also produced by the monitoring system for the purposes of ensuring good quality physics data collection is maintained.

The system is designed to be flexible and provide prompt feedback for those operating the experiment. It was thus included as part of the DAQ (Data Acquisition) system, lbne-artdaq, discussed in Sec. 5.1. The monitoring framework itself is the subject of Sec. 5.2, with its two functions, data quality monitoring and producing online event displays, presented in Sec. 5.3 and Sec. 5.4 respectively. Finally, the web interface developed to allow synchronisation of this monitoring data to a dedicated web page for ease of access is briefly described in Sec. 5.5.

5.1 The DAQ Framework

Experiments at FNAL are moving over to using artdaq, a centrally-maintained data acquisition system built on the art framework utilised by all offline software written for experiments hosted at the lab. The DUNE 35ton experiment was one of the first to use this new software (may be the first... but uBooNE and LArIAT possibly use it... I'll check!) and used an experiment specific system named lbne-artdaq [1]. A general overview of lbne-artdaq is shown in Fig. 5.1.

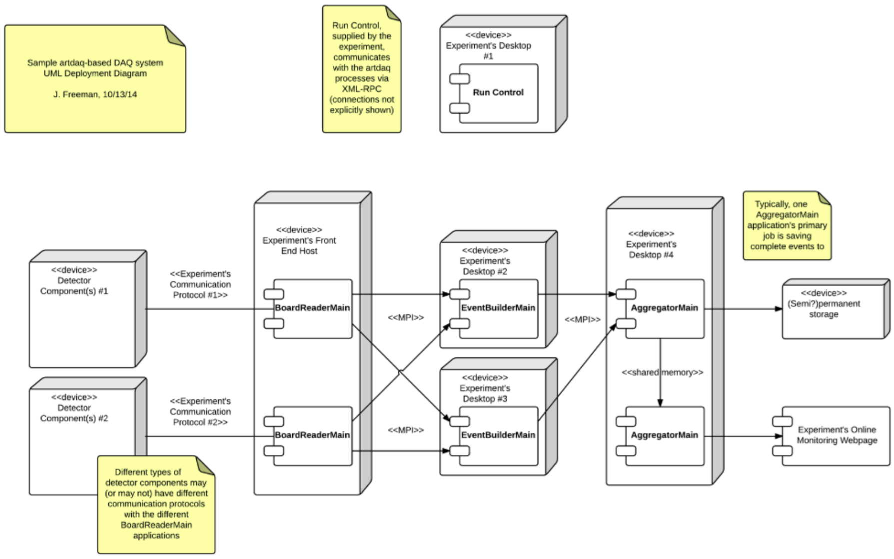


Figure 5.1: Overview of the lbne-artdaq framework used for data acquisition by the DUNE 35ton experiment. See the text for a complete description. [Thank John Freeman for this image... how to reference?]

Data flows from left to right and pass through components common to most DAQ systems. Closest to the detector components (i.e. the RCEs, SSPs and PTB [see Sec. ??]) are the board readers which take the output from the firmware as soon as it is ready and sends it downstream to the event builders. There exists a board reader for each of the detector components (totalling 24) and each is unaware of the existence of the others. It is the job of the event builders to assemble a full 'event' from these individual 'fragments' passed on from each of the detector elements. An event is complete once composed of a full set of '`artdaq::Fragments`' and the event builders will wait to receive them all before sending the data onwards to the aggregators.

There are two aggregators which take the full events but process them in very different ways. All the data passes through only the first aggregator, whose function it is to write the output to disk and thus end processing by the DAQ. The second aggregator receives no events but instead has access to the shared memory occupied by the data as it passes through the first

[1] Since the formation of the DUNE experiment occurred only a few months before the running of the 35ton, all online software maintained the use of the outdated 'lbne' descriptor to prevent unnecessary potential problems associated with large scale code changes and alleviate the risk of further delays. It should be again stressed that the 35ton was recognised by the DUNE collaboration as an integral part of the DUNE plan and the use of *lbne* was in no way an indication of a project associated only with the dissolved previous experiment!

aggregator; it is thus designed specifically for the purpose of monitoring and in no way affects the data or the output from the first aggregator. It is within this second aggregator process that the online monitoring system described in the proceeding section is designed to run.

Each of the DAQ processes runs on a machine on the private DAQ network and is configured as normal within art (using the *fhicl* (Fermilab Hierarchial Configuration Language) configuration language). Two nodes on the main FNAL network (lbne-gateway01/02) provide access to these private machines, of which there are 7 (lbnedaq1-7), and contain all scripts and setup necessary to run through the DAQ via a command line interface.

5.2 Online Monitoring Framework

The framework developed for the monitoring system had the following desgin goals:

- to be able to analyse the data read out of memory it in its raw 'DAQ format';
- to be as computationally efficient as possible to allow for processing at the event rate (data taking rate);
- to provide the flexibility for further monitoring plots to be added with ease;
- to allow for use of an online event display to provide comprehensible images of the raw data.

In general, the final developed system succeeded in all these goals and provided invaluable information, becoming an integral tool in the commissioning and the data taking of the 35ton. An illustration of the framework is shown in figure 5.2.

5.2.1 Monitoring Framework Design

The setup consists of a central 'module', `OnlineMonitoring_module.cc`, which is configured within the art framework through its base class. The OnlineMonitoring class controls the running of the system and owns instances of further classes, each designed for a specific purpose, controlling the data flow by calling the relevant methods when required. Once an event has been obtained, the data for each component is processed and repackaged into RCEFormatter, SSPFormatter and PTBFormatter objects. The purposes of this method are thus:

- to provide an interface between the raw data and the methods which analyse the data. This is important as it provides a single point of maintainance for when formats change and allow for various 'DAQ modes' to use the same analysis code;

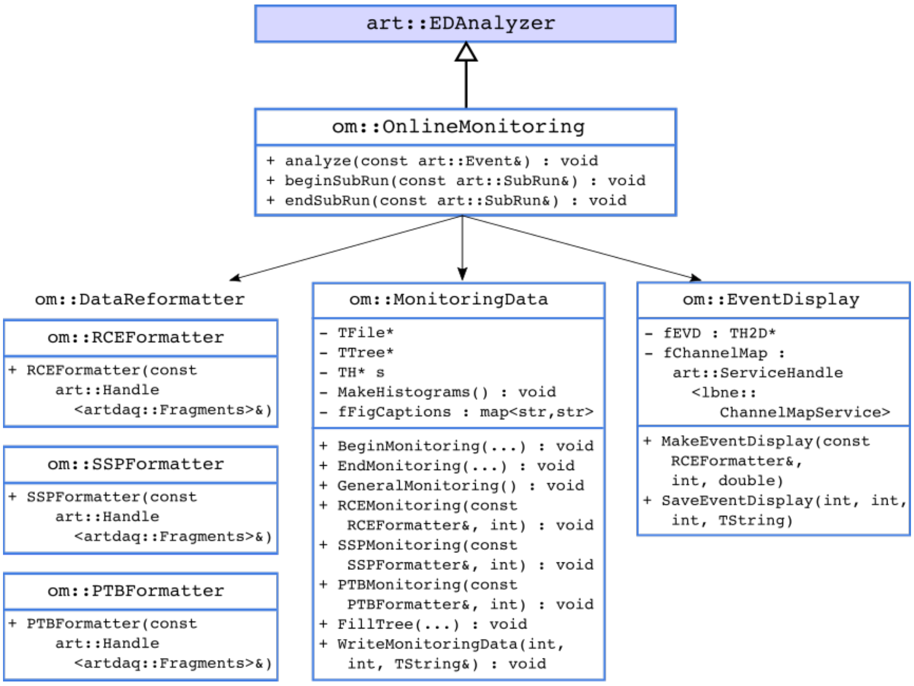


Figure 5.2: Demonstration of the framework designed for online monitoring in the DUNE 35ton experiment.

- to separate interaction with the DAQ from the handling of output data objects;
- to fascilitate jumping around the data for more detailed analysis which would not be possible if just looking through linearly.

The main drawback to performing this step is it requires all the data to be held in memory until the end of the event and represents basically the same information as initially present. However, it was decided the advantages were worth the compromises in memory useage required and no problems were apparent during the course of the run except when operating at the very limits of the capability of the DAQ.

These reformatted data objects are then passed to the methods in the MonitoringData class for straight forward anaylsis. This class owns all of the data products which are output from the monitoring (e.g. histograms, graphs, trees and files) and deals with their filling and writing out when required. This is discussed further in Sec. 5.3.

The event display is handled by its own dedicated class, EventDisplay; this has methods for making the displays and saving them as an image in the correct place when required. It is designed to accept the reformatted RCE object and presents the data in as meaningful way as possible; this is detailed fully in Sec. 5.4.

5.2.2 Writing Monitoring Data

The data objects are created new for each subrun and are written out at three points during data taking:

- an initial write out N seconds after the start of the subrun;
- at frequent intervals during the subrun, every M seconds;
- at the end of the subrun.

The parameters N and M are user defined and were set to 30 and 500 resepectively for normal data taking. The data products are only cleared at the end of a subrun, so any intermediate writing out of data simply refreshes the current plots.

The event displays are computationally expensive to make and so were only created once per subrun during normal running. However, since a subrun was automatically stopped by the DAQ and a new one started once the output file had reached 5 GB in size, and (since zero suppression was not utilised at any point during the run) this occurred on average every four minutes, a new event display was made every few minutes.

All the output data are saved on a shared disk on the gateway DAQ machines for further use. This is discussed in Sec. 5.5 below.

5.2.3 Configuring the Monitoring

[Possibly don't need this section...] The system was designed to be flexible and many parameters were available to control the running of the monitoring. These are listed and described below, with default parameter provided in brackets.

- TPCModuleLabel ("daq") – art module label for TPC data saved in the DAQ;
- PhotonModuleLabel (["sparseSsp", "daq"]) – art module label for photon data saved in the DAQ;
- TriggerModuleLabel ("daq") – art module label for counter data saved in the DAQ;
- DetailedMonitoring (false) – fills more, and usually more computationally expensive, data;
- ScopeMonitoring (false) – support for a different DAQ running mode, 'scope mode';
- DataDirPath ("/storage/data/") – path at which the data files are saved by the first aggregator;

- MonitorSavePath ("/data2/lbnedaq/monitoring/") – location to save DQM data;
- EVDSavePath ("/data2/lbnedaq/eventDisplay/") – location to save event displays;
- PedestalFile ("/data2/lbnedaq/pedestal.csv") – location of the most recent pedestal file, containing pedestals for all channels. This was used for pedestal subtraction when making event displays;
- ImageType (".png") – the format to save any images;
- MonitoringRefreshRate (500) – how often to write out the most recent monitoring data plots;
- InitialMonitoringUpdate (30) – how long after starting a new subrun to initially write out the data;
- EventDisplayRefreshRate (60) – how often to refresh the event display when not just making one per subrun;
- LessFrequentFillRate (20) – how often to fill the more computationally expensive plots;
- DriftVelocity (0.9 #mm/us) – rough drift electron velocity, used for calculating the x coordinate for the event display;
- CollectionPedestal (550) – the default pedestal value if the file isn't readable;
- MicroslicePreBuffer (5) – how many microslices are saved by the RCEs before the one containing the trigger;
- MicrosliceTriggerLength (5) – the length of the trigger.

5.3 Data Quality Monitoring

The overarching aims of the online monitoring system was to provide direct feedback informing the operators of the quality of the data being taken. This is vital for various different aspects of data taking, for example

- ensuring all detector components being used in the currect run are receiving and sending on data;

- noting the TPC readout has entered the 'high noise state' and acting accordingly; [MW: I will probably have explained what this is in a previous chapter!]
- checking the trigger rates from the external cosmic muon counters are feasible;
- etc.

The monitoring was diagonalised in a similar way to the DAQ readout with data from the TPC, photon detector and external counters processed separately.

5.3.1 TPC Monitoring

Ensuring the high quality of TPC data involved mainly considering various distributions of the ADC values provided by the front-end boards, separated by channel, board and APA. The mean and RMS of the ADC values for a given channel provides information such as the measured pedestal and the level of noise being read out. The uncorrelated component of the noise can be monitored using the concept of 'DNoise'; this considers the difference in ADC value between two neighbouring channels at a given readout time and represents the level of noise which would be impossible to remove by the use of coherent noise filters only. Unfortunately, for the 35ton, this uncorrelated component made up most of the noise across all channels (see Fig. 5.3a). FFTs of the signal waveforms, performed separately for each RCE, were also useful in monitoring bands of noise in frequency space.

Monitoring of various other problems, such as the digitiser stuck code issue, synchronisation concerns resulting in a different number of microslices being saved in corresponding RCE millislices, and the asymmetry of bipolar pulses, were added as these issues became apparent during the commissioning.

5.3.2 Photon Detector Monitoring

Analogously to the TPC situation, monitoring of the photon detectors mainly involved considering various ADC distributions separated by optical channel and by detector. The peak height, pedestal and integral of each waveform were also considered as a function of channel to ensure each were operating consistently.

The triggers sent on by the SSPs were also studied; unfortunately due to the design of the monitoring framework (with it not guarenteed to receive each event), trigger rates were challenging to compute. Eventually, it was decided to leave them in the monitoring but only consider the relative rates – the monitoring code was used offline, processing closed files, to ensure all events are considered and determine accurate rates. Along with the trigger rate, the number of triggers, the fraction of events containing a trigger and the number of readout ticks within each trigger were also considered.

During installation, one photon detector was erroneously left unconnected to its SSP and so was unavailble during the run. This was spotted using the online monitoring – unfortunately after the cryostat had been sealed however!

5.3.3 External Counter Monitoring

Since monitoring the external counters primarily involves considering trigger rates, a similar problem to that encountered in the photon detector monitoring was faced. A similar solution was agreed upon and the trigger rates were only considered relative to different counters. For each counter, the hit rate and the average activation time were monitored to ensure counters in similar positions were recording similar cosmic muon data. The number and type of payloads sent on from the PTB were also detailed so the amount of data, along with information about what the data are comprised of, can be monitored.

5.3.4 General Monitoring

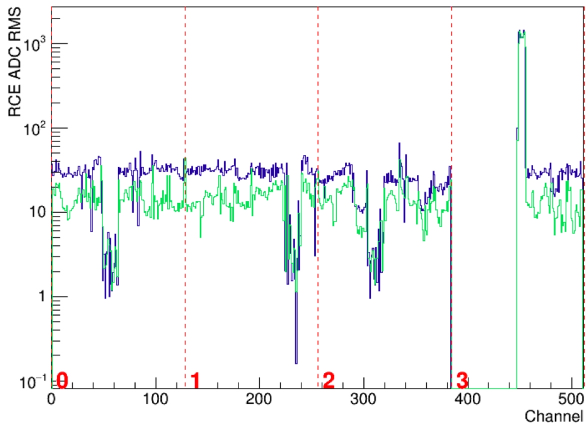
A variety of useful quantities not pertaining to any specific subcomponent were also monitored to assure smooth data taking. These include the size of output files from recent runs, the average event size from recent runs, information about which detector subcomponents are taking data and the number of events seen by each and also synchronisation information between various detector components.

5.3.5 DQM Plots

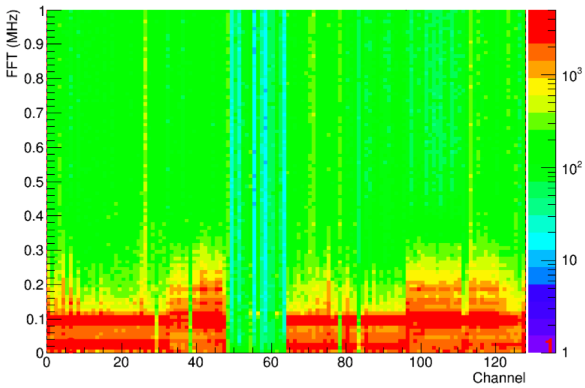
The DQM section of the online monitoring produced around 60 figures each time it is run, illustrating the data discussed in the previous sections. It is unnecessary to reproduce many here [perhaps an appendix? I think unnecessary though] but a sample for reference are shown in Fig. 5.3.

5.4 Online Event Display

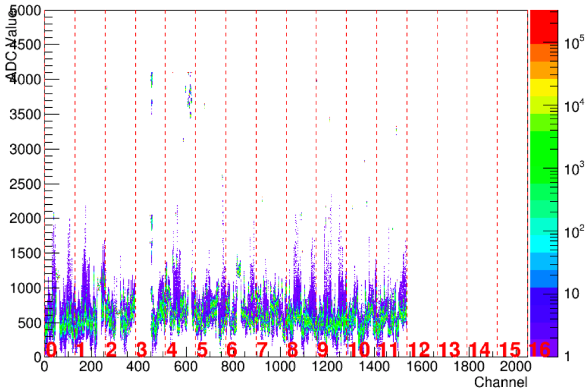
One of the highlights of being in ROC West (Remote Opertation Control room at FNAL) during data taking was watching the online event display refresh with updated images representing



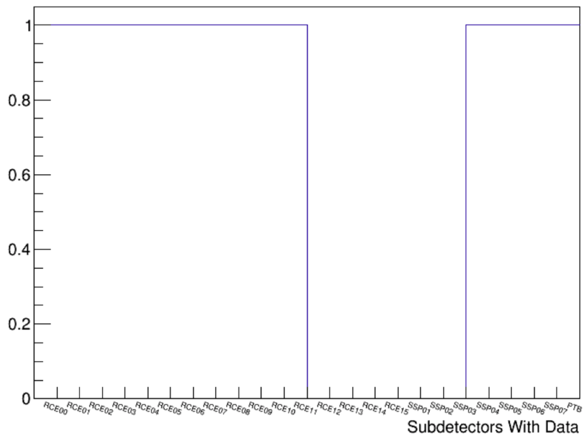
(a) TPC noise. The total noise (RMS of the ADC values) is shown in blue and the uncorrelated component of this noise is shown in green. This is determined by considering the 'DNoise', the difference in ADC between neighbouring channels for any given tick.



(b) FFT of the waveform read out by the first RCE (channels 1–128).



(c) ADC values as a function of channel; incredibly useful plot containing the mean and RMS for all channels together.



(d) Subdetectors which are successfully collecting data. In this particular run, it can be seen one quarter of the TPC readout was turned off, along with three photon detector readouts.

Figure 5.3: Demonstration of various plots used in the Data Quality Monitoring for the 35ton. [Images are probably placeholders at the moment and should be reconsidered.]

cosmics passing through the detector. Watching tracks appear in the data represented such a hugh acheivement for the DUNE 35ton operations team it never failed to cause excitement every time a new event appeared. The event display also allowed for an incredibly straight forward way of monitoring the data – high noise states, poor LAr purity and drift field problems were all immediately evident from the display.

Given the way in which data were read out of the detector, it proved challenging finding a way to represent this in a simple way that was comprehensible. The construction of such a display is the subject of this section.

5.4.1 Selecting the Data

[The data format will likely be described in the 35ton section – most of this will probably be moved up to that point and referenced at a later stage...]

The raw format for the TPC data is complicated and has many levels of structure. Refer to Fig. 5.4 during the following description. The 2048 channels are readout out by 16 front-end boards (containing the cold electronics, including the digitisers), each processed by an RCE and then read into the DAQ by a board reader. The format at this point is referred to as a millislice; there is a millislice for each of the detector components (RCEs, SSPs and PTB) and an 'event' is a collection of all such millislices. For the TPC data, a millislice contains all the information for 128 channels. This data also has further substructure; a millislice is composed of N microslices, with each microslice containing M nanoslices. A nanoslice contains 128 ADC values, representing one 'tick' (== 500 ns) worth of data for 1/16th of the detector. A microslice thus contains this information for a 'drift window' (M ticks) and a millislice a collection (M) of drift windows. For the normal data running, N was set to 20 and M 1000.

As the detector collects data, the RCEs continually create and save microslices to send to the DAQ to form a millislice. These microslices are empty (contain no nanoslices) until a trigger is received, at which point nanoslices are made and saved within each microslice. There is also a buffer in place to save a certain number of full microslices (microslices containing nanoslices) before the microslice containing the trigger. A certain number of full microslices proceeding the trigger are also recorded by the RCEs. During normal running, a '4 + 1 + 10' format was employed; four microlices containing nanolices before the trigger was recieved, the microslice containing the trigger, and the ten following microslices. It should be further noted that, since the DAQ was designed for continuous data readout, these microlices need not necessarily be within the same millislice: it is possible for the trigger to occur in microslice 18

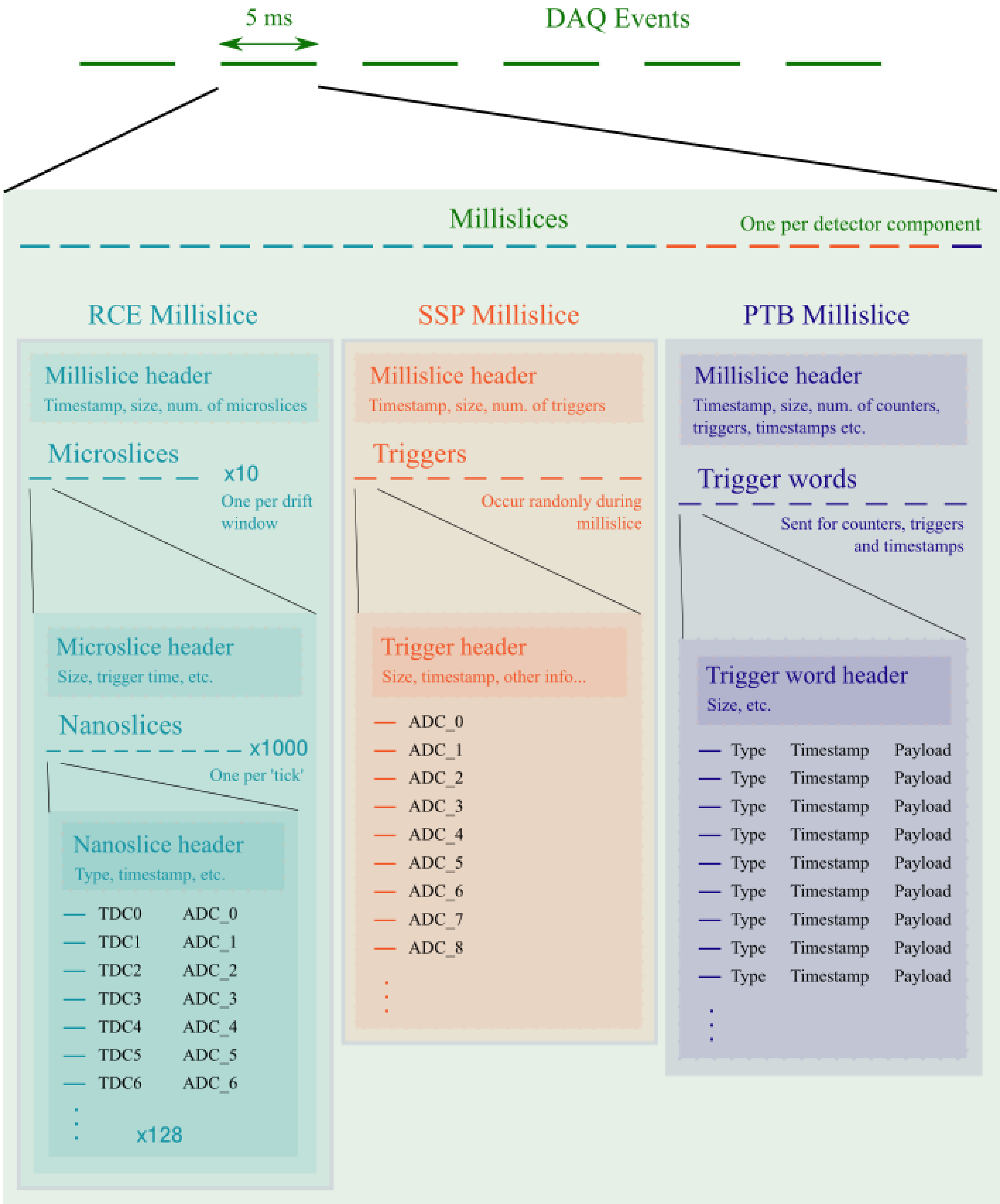


Figure 5.4: Demonstration of the format used in 35ton raw data. A 'DAQ event' is composed of a single milliclice from each component, each containing further substructure unique to the readout elements. See the explanation in the text for further details. [The image is possibly confusuing – can remake if necessary.]

of a certain millislice, resulting in the 15 filled microslices straddling successive millislices. This is demonstrated in Fig. 5.5.

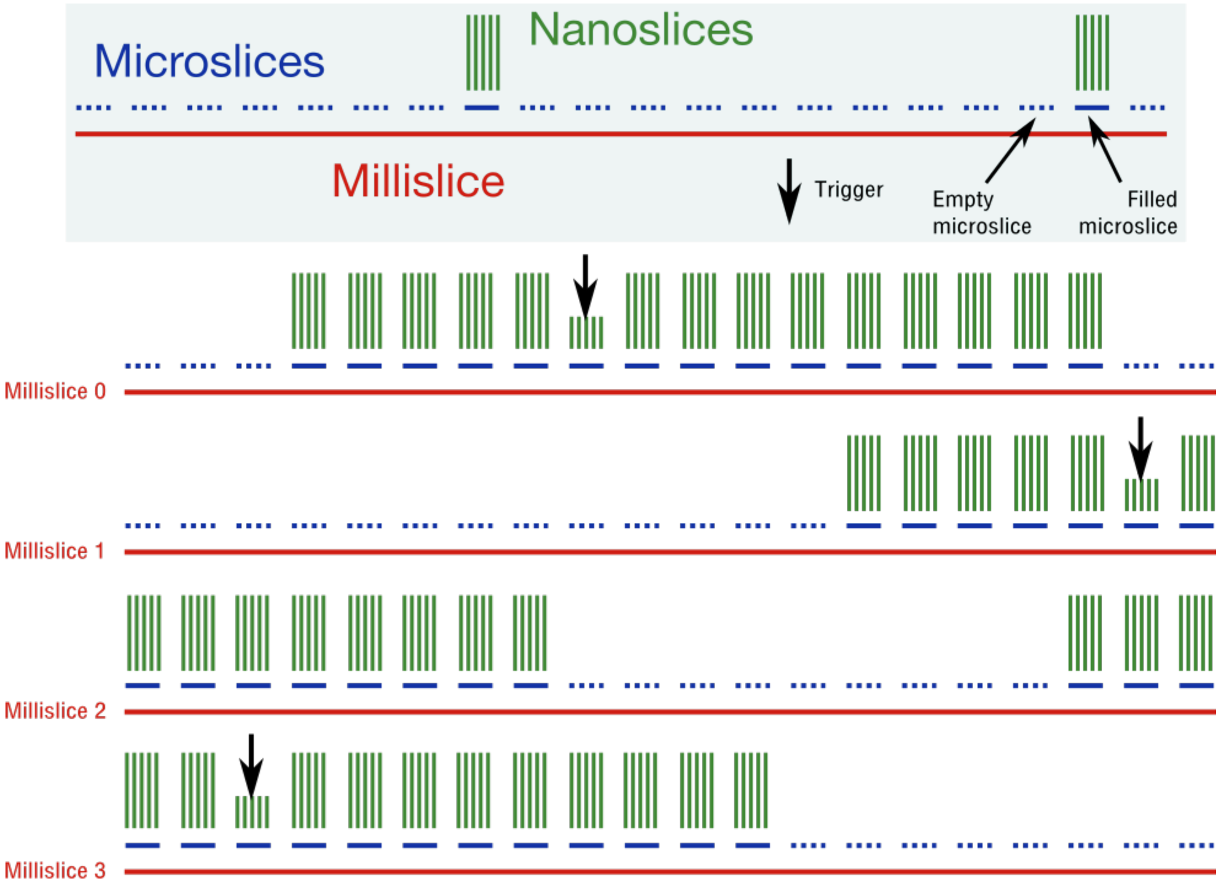


Figure 5.5: Demostration of how TPC data is saved when using a DAQ designed for continuous readout. The black arrows represent hypothetical triggers occurring within the duration of a particular millislice. In each case, the 4 preceeding microslices and the 10 proceeding microslices are filled with nanoslices and saved; all other microslices are saved with no nanoslices since they contain no useful data. An example of such an event is shown occurring in millislice 0 in the figure. As described in the text, a trigger can cause the useful microslices to straddle consequetive millislices; this is represented in the following millislices in the figure.

Note this also results in real 'physics events' being saved in separate 'DAQ events'; for this reason a splitter/stitcher module has been designed to extract the actual triggered events from the raw data and repackage them into a useful event structure – this is the first stage before all offline analysis with the 35ton data.

Since the event display runs online, a subtle selection must be applied to ensure the full physics event occurs within the current DAQ event; proceeding and preceeding events are unaccessible to the DAQ during running. This is achieved by noting whether or not a trigger occurred (i.e. microslices contain nanoslices) when reformatting the RCE data in DataReformatter, and which microslice it occurred in. For the event display, a triggered event is only useful if the trigger occurred within a certain range (e.g. microslice 5 to microslice 10); this ensures all the filled microslices are present within the current millislice. The event displayed is then filled for a given range of microslices around the trigger to capture all the actual physics data.

5.4.2 Representing the Data

[This section requires background of reconstruction – this will be the previous chapter.]

Due to the wrapped nature of the induction wires in the 35ton, and disambiguation impossible without full reconstruction, it makes little sense to look at charge deposited on these planes. This results in only the collection planes being useful for showing the data in this way, meaning just one dimension. A second dimension is possible if the view is changed to show a representation of the TPC from above and using the drift time as a coordinate. This requires the two centre APAs be shown together as one combined readout structure. A 'global collection wire' is defined by numbering the wires across the APAs, leaving a space for the gaps inbetween, and used to represent the dimension across the TPC. The drift time, in ticks, represents the second spacial coordinate once charge collected in the short drift volume has been corrected to a negative tick.

By working with the system used to record pedestal values of the channels, it is possible to perform an approximate pedestal subtraction on the data. Whenever a pedestal run is performed by a shifter, a text file containing all the calculated pedestal values for each channel is created and subsequently uploaded to a database for offline use. By making sure a copy of the most recent pedestal file is always available to the monitoring framework, it is possible to always represent the charge as accurately as possible. It is then ensured the pedestal-subtracted ADC values are within the range $0 - 250$ to limit the noisy channels and correct for any accidental negative charge. Finally, given the relatively low signal-to-noise ratio, it was decided a greyscale image showed the best resolution for seeing tracks traverse the cryostat.

An example event display is shown in Fig. 5.6.

5.5 Monitoring Web Interface

The output of the monitoring is vital in assuring the experiment continues to take high quality, analysable data. To facilitate the monitoring, a web interface has been developed to enable

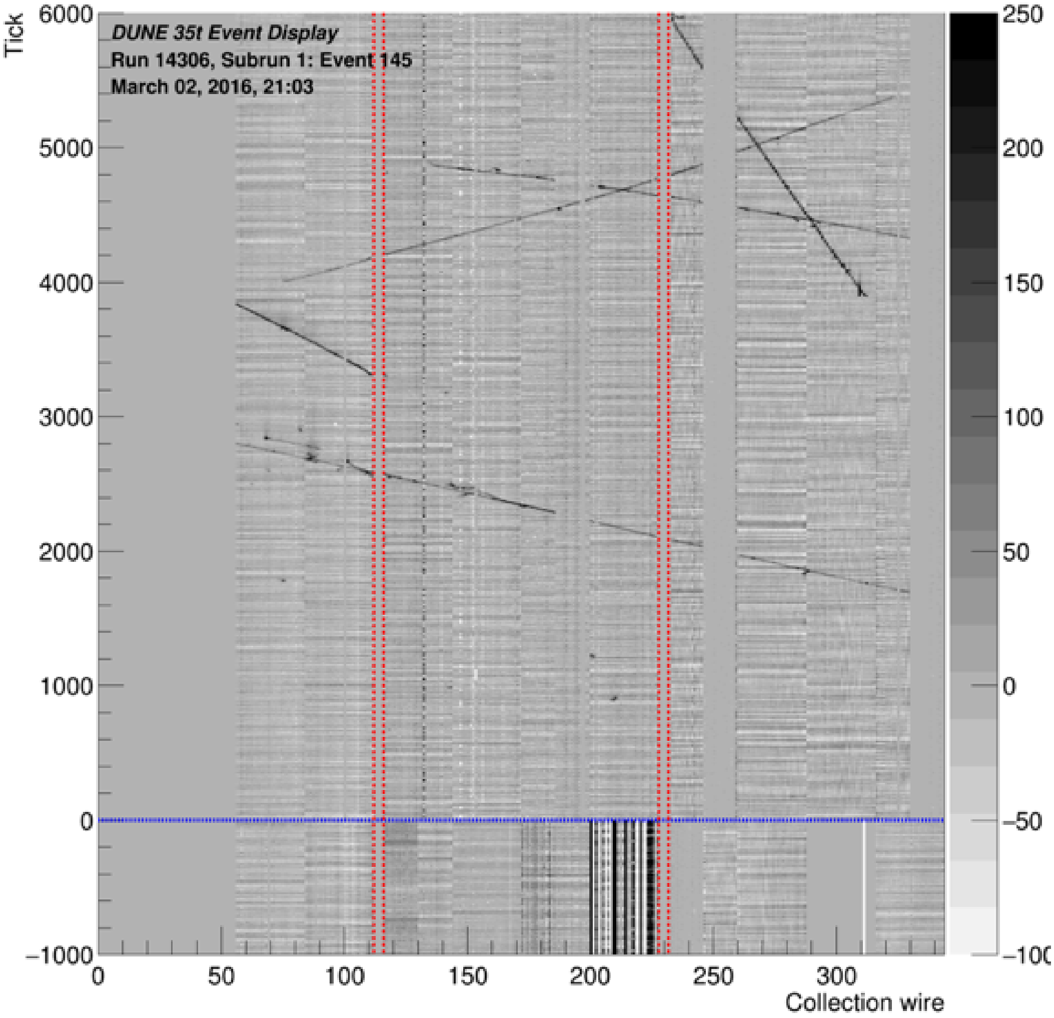


Figure 5.6: Example online event display made as part of the online monitoring framework for run 14306 (2nd March, 2016). The view is from the top of the detector looking down; the red lines represent the spaces between the APAs and the blue line the location of the APA frames, separating the long and short drift regions.

all useful information to be displayed on the web and allow convenient, universal access. This inferface, along with the complementary web page, is relatively basic but certainly functional and delivered all expected of it for the purposes of a short prototype run. The method of automating the transfer of the monitoring data from where it is saved by the DAQ process to somewhere accessible by the web server is briefly described in Sec. 5.5.1 and the web page itself discussion in Sec. 5.5.2.

5.5.1 Automated Data Transfer

The most complicated part of the web interface is ensuring the monitoring output is available in the correct place when needed. This is achieved using a combination of disk mounting and automated scripts, demonstrated in Fig. 5.7.

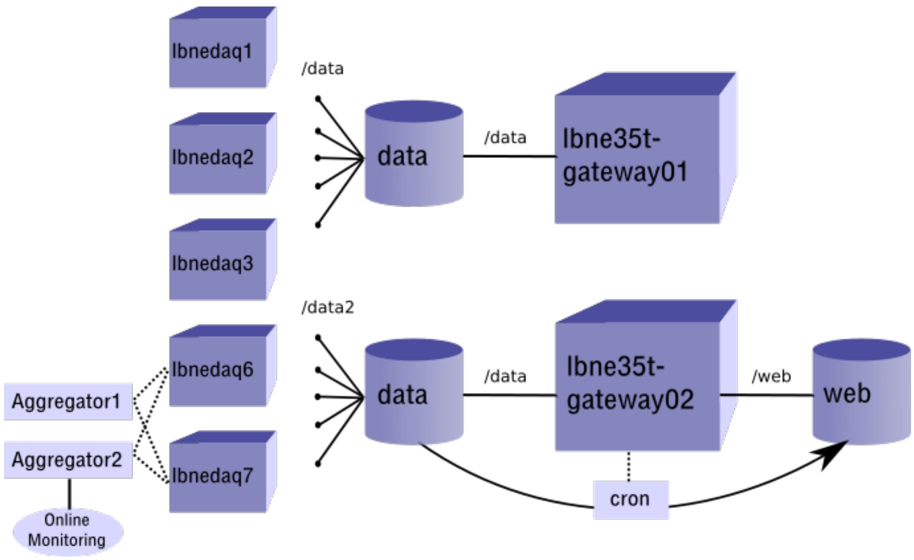


Figure 5.7: Schematic showing the interface between the online monitoring system and the web. The DAQ machines are shown as rectangles with their disks represented as cyliners. Connections between a node and a disk are shown as straight lines, with dotted lines representing processes running on the machine.

The DAQ aggregator processes run on the lbnedaq6 and lbnedaq7 nodes, requiring any saved output be put in a place which is accessible to these machines. The solution which was developed was to mount a data disk belonging to lbne35t-gateway02 onto these private nodes and save all relevant information there. The constraints placed on the setup by the DAQ group, which preferred nothing other than DAQ processes to run on lbne35t-gateway01, required a second gateway node to be utilised to move the files off the private network. Using lbne35t-gateway02 also allowed the Fermilab web area to be mounted, with an automated job utilised to copy the monitoring output from the data disk to the specific area on the web server. The frequency of this job, 30s, defined the maximum latency one could expect between data being written out and images appearing online.

5.5.2 Web Page

The web page was hosted at FNAL and located at lbne-dqm.fnal.gov. The method in the monitoring framework used to write out all the ouput also wrote and saved all the html used to allow images of the plots to be displayed on the web. This html is copied, along with all the images and data files, to the web area as discussed above in Sec. 5.5.1. The web page was basic but performed all required for use in the 35ton; it had dedicated pages for all the data quality monitoring information and the online event display (the nearline monitoring was also hosted at this website but is not described here). See Fig. 5.8 for a demonstration of web page and example navigation.

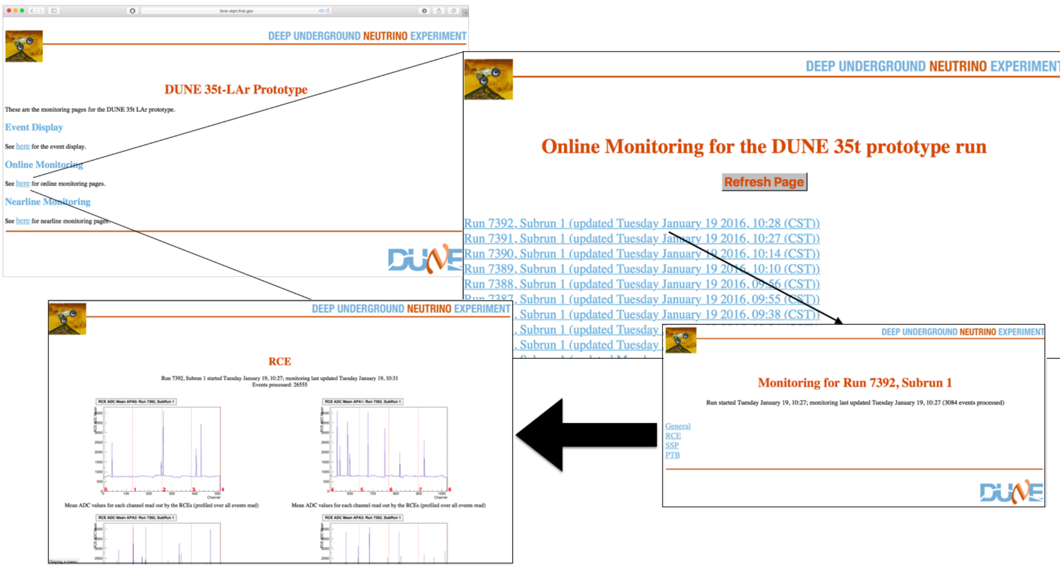


Figure 5.8: Demonstration of the web page developed to display information produced by the online monitoring and event display. The pages are written in basic html but allowed prompt and convenient feedback directly from the DAQ be accessed anywhere and assist in remote monitoring of the experiment. All previous runs are also kept on the website for reference.

5.6 Online Monitoring Summary

The monitoring, with web support, was imperative for the success of the 35ton. During the ongoing vertical slice tests during summer 2015, the majority of the setup was in place and enabled progress in testing and signing off the APAs to be completed months faster than it otherwise would have been. During this time, and also during commissioning, this framework was the only way of analysing the data without reading it into LArSoft and writing specific software. Overall, the framework provided essential feedback and contributed positively towards DAQ uptime during the data taking period. It is currently in the process of being adapted for future use in DUNE, specifically as part of the protoDUNE DAQ for the run in 2018.

Chapter 6

Reconstruction in a Liquid Argon TPC

Chapter 7

Detection of π^0s in 35t

Chapter 8

Electron Reconstruction for ν_e Oscillation Signal at the DUNE Far Detector

Chapter 9

Summary

Bibliography

[1] S. Amerio et al. "Design, construction and tests of the ICARUS T600 detector". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 527.3 (2004), pp. 329–410. ISSN: 01689002. DOI: 10.1016/j.nima.2004.02.044.

[2] A. Curioni et al. "A regenerable filter for liquid argon purification". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 605.3 (2009), pp. 306–311. ISSN: 01689002. DOI: 10.1016/j.nima.2009.04.020. arXiv: 0903.2066 [physics.ins-det].

[3] Alan Hahn et al. "The LBNE 35 Ton Prototype Cryostat". In: (2014).

[4] David Montanari et al. "First scientific application of the membrane cryostat technology". In: 1664.2014 (2014), pp. 1664–1671. DOI: 10.1063/1.4860907. URL: http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.4860907.

[5] David R Nygren. "The Time Projection Chamber - A New 4pi Detector for Charged Particles". In: *eConf* C740805.PEP-0144 (1974), pp. 58–78.

[6] Carlo Rubbia. *The Liquid Argon Time Projection Chamber: A New Concept For Neutrino Detectors.pdf.* 1977.

[7] Terry Tope et al. "Extreme argon purity in a large, non-evacuated cryostat". In: 1169.2014 (2014), pp. 1169–1175. DOI: 10.1063/1.4860838. URL: http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.4860838.