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# NO$\nu$A Data Acquisition System

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**Abstract**

The NO$\nu$A (NuMI Off-Axis $\nu_e$ Appearance) experiment is a long-baseline neutrino experiment using the NuMI main injector neutrino beam at Fermilab and is designed to search for $\nu_\mu$ ($\bar{\nu}_\mu$) to $\nu_e$ ($\bar{\nu}_e$) oscillations. The experiment will consist of two detectors; both positioned 14 mrad off the beam axis: a 220 ton Near Detector to be located in an underground cavern at Fermilab and a 14 kton Far Detector to be located in Ash River, MN, 810 km from the beam source. In addition, a prototype Near Detector is currently in operation in a surface building at Fermilab. The detectors have similar design, and consist of planes of PVC extrusion cells containing liquid scintillator and wavelength shifting fibers. The fiber ends are readout by Avalanche Photodiodes (APDs). The primary task for the Data Acquisition (DAQ) system is to concentrate the data from the large number of APD channels (360000 channels at the Far Detector, 16000 channels at the Near Detector), buffer this data long enough to apply an online trigger, and record the selected data. The concentration of data is accomplished through the use of a custom hardware component Data Concentrator Module (DCM). The intermediate buffering of the data is accomplished through a computing buffer farm, in which each node runs software to apply an online trigger to a time slice of data received from the DCMs. Data correlated with the beam spill time as well as random data samples for calibration purposes and events with interesting topology may be selected by the online trigger. In addition to those components involved in managing the data flow, the DAQ system consists of components for control, configuration, monitoring and timing. The design of the DAQ system, with emphasis on the DAQ software, will be discussed as will experience with its deployment on the prototype Near Detector.

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*Keywords:* Data acquisition

## 1. Introduction

The NO$\nu$A (**N**uMI **O**ff-Axis $\nu_e$ **A**ppearance) experiment[1] is a long-baseline neutrino oscillation experiment currently under construction at Fermilab and in northern Minnesota. Using the NuMI main injector neutrino beam at Fermilab, upgraded to 700 kW of beam power, the experiment will search for $\nu_\mu$ to $\nu_e$ and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations with goals of measuring the oscillation mixing parameter $\theta_{13}$ to an order of magnitude better than existing measurements; potentially determining the neutrino mass hierarchy and constraining the neutrino mixing CP violation phase; and performing precision measurements of $\Delta m^2_{32}$, $\theta_{23}$, $\Delta\bar{m}^2_{32}$, and $\bar{\theta}_{23}$.

The experiment will consist of two detectors; both positioned 14 mrad off the beam axis: a 220 ton Near Detector (ND) to be constructed in an underground cavern at Fermilab and a 14 kton Far Detector (FD)

[1]For the NO$\nu$A DAQ Group and the NO$\nu$A Collaboration

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to be constructed in Ash River, MN, 810 km from the beam source. The NOvA detectors are designed to be functionally equivalent to facilitate cancellation of systematic errors due to beam flux and cross-section uncertainties.

The readout of the first FD block is expected in early 2012, and beam upgrades and ND cavern excavation will begin shortly afterwards. The experiment will be fully operational by early 2014. A prototype version of the ND, NDOS (**N**ear **D**etector **o**n the **S**urface), was completed in March, 2011 and is currently in operation at Fermilab.

## 2. NO$\nu$A Detectors

The NO$\nu$A detectors consist of planes of PVC extrusion cells[2][3] in alternating horizontal and vertical orientations as shown in Figure 1. The plane cells are filled with liquid scintillator and a Wave Length Shifting (WLS) fiber running the length of each cell and looped at the end of the cell as shown in Figure 2. Both ends of the WLS fiber are read out by one pixel of a 32-pixel Avalanche Photodiode (APD). The APD is operated at a gain of 100 and cooled to $-15°C$ for a dark noise of 2 photoelectrons.

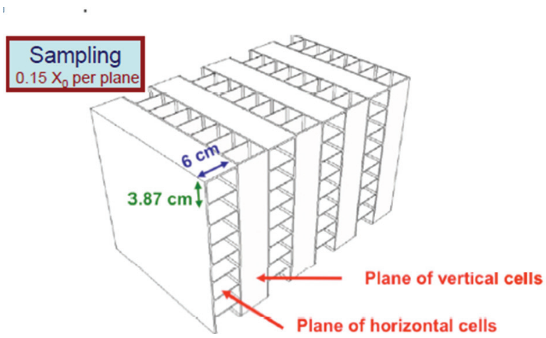


Fig. 1. Illustration of the detector layout.

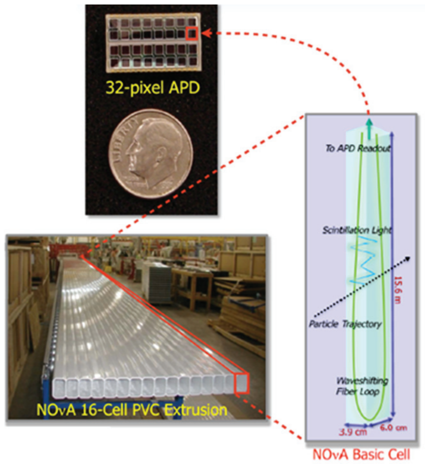


Fig. 2. Detector technology used in NO$\nu$A.

The FD building, shown in Figure 3, reached beneficial occupancy in April, 2011 and is currently being outfitted for detector construction and operation. As shown in Figure 4 the FD will have dimensions of 15.6 m x 15.6 m x 63 m, a mass of 14 kton, and consist of 930 planes with 360000 readout cells. Because the FD has only a small amount of shielding from cosmic rays, equivalent to about 10 radiation lengths, and a large surface area, it will be subject to a high cosmic ray muon rate of 200 kHz.

Fig. 3. Photo of Far Detector building and site.

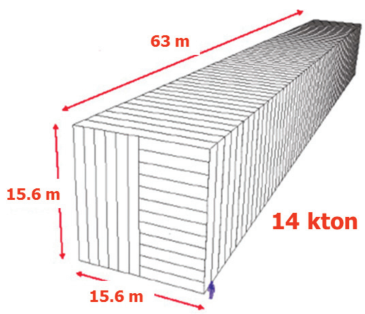


Fig. 4. Sketch of Far Detector.

The ND has a mass of 0.22 kton and will be constructed approximately 1 km downstream of the NuMI beam target at a depth of 100 m below ground level. It will consist of 196 scintillator planes followed by 10 steel/scintillator plane pairs acting as muon catcher, for a total of 16000 readout cells. The ND location underground will suppress the cosmic ray muon rate to a modest 50 Hz. However, the ND, being much closer to the beam source, will have a much higher in-spill data rate relative to the FD. The in-spill neutrino interaction event rate at the ND is expected to be 24 neutrino events interactions per 10 $\mu$s beam spill including both neutrino interactions which occur in the detector and those which occur upstream of the detector in the rock and produce hits in the detector.

A prototype version of the ND, NDOS[4], is in operation at Fermilab now and is operating in a position to receive neutrino interactions from both the NuMI beam (6.4° off-axis) and Booster beam as shown in Figure 5. A photo of NDOS is shown in Figure 6. NDOS has been an invaluable tool for commissioning and debugging the DAQ system.

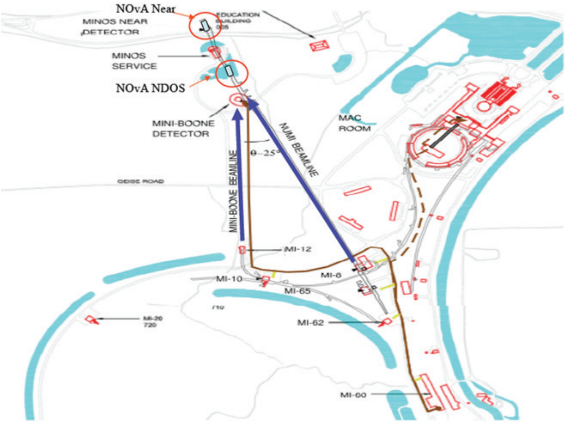


Fig. 5. The position of NDOS and ND in the Booster (Miniboone) and NuMI beamlines. NDOS is operating in a surface building, and the ND will be constructed in a cavern 100 m below the earth's surface.

Fig. 6. A photo of NDOS.

## 3. DAQ System

The NOvA DAQ System design has been driven by the goals of the experiment, which require the DAQ system to capture and record the following types of events:

- *Beam Neutrino Events.* These events are generated in 10 $\mu$s beam spills at a period of 1.3 s. To correlate data with the beam spill, the DAQ system has available to it a beam spill signal sent via the accelerator network at Fermilab. This is used to create a trigger consisting of a time stamp and a time window which is generated at the ND and transmitted to the FD via the Internet.
- *Calibration Data.* Randomly sampled data will be recorded for calibration purposes at a rate which is 100x the beam spill data. Cosmic ray muons will be recorded as part of this randomly sampled data.
- *Other Physics Events of interest.* Although not the primary goal of the experiment, other physics events of interest might include supernova neutrino events, magnetic monopoles and high energy cosmic ray neutrino events.

These design goals have been met with a DAQ system which has front-end electronics which reads out continuously with no dead time, and a downstream buffer farm in which data can be stored for 20 seconds or more while waiting for either a spill trigger or a decision regarding whether or not an interesting physics event has occurred.

### 3.1. DAQ Overview

A block diagram of the overall DAQ system is shown in Figure 7. The data flow in this diagram is from

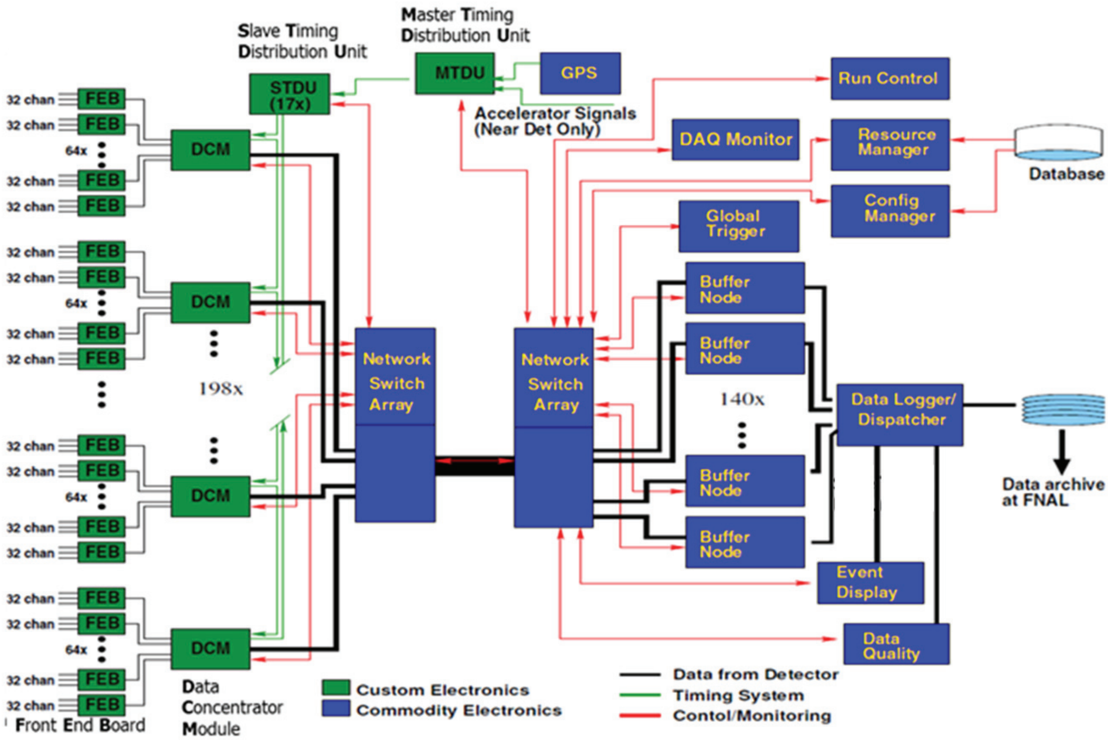


Fig. 7. Schematic overview of the DAQ system. The number of components is shown for the FD DAQ system and will be scaled down for the smaller ND with fewer channels to be read out.

left to right beginning with the 32 channels on the left representing the 32 pixels of the APD, and ending with the Data Logger writing data to disk on the right. The Front End Boards (FEB), Data Concentrator Modules (DCM) and Master and Slave Timing Distribution units (MTDU and STDU) are custom electronic components designed specifically for NO$\nu$A, while all other components are commodity electronics running NO$\nu$A specific applications.

### 3.2. Front End Boards

There are approximately 12000 FEBs in the FD DAQ system, with each FEB responsible for reading out the 32 pixels from one APD. A schematic of an FEB is shown in Figure 8. The FEBs are operated in triggerless, continuous readout mode with no dead time. As shown in the figure, the ASIC on the FEB provides amplification and shaping of the signal followed by multiplexing to an array of ADCs on the FEB for digitization. The digitization is performed on each channel at a rate of 2 MHz at the FD, and 8 MHz at the ND, where the higher time resolution at the ND is required because of the much higher neutrino interaction rate during the beam spill at the ND.

The FEB FPGA applies a Digital Signal Processing (DSP) algorithm to select signals above a configurable pixel-by-pixel programmable threshold for each channel and extract the pulse height and timing edge for the signal. The timing resolution determined by the DSP can be better than the digitization period using a Matched Filtering algorithm in which the raw data response is matched to an ideal response function in the FPGA. The DSP algorithm to be used at the FD and ND is under development, while the algorithm used at NDOS is a simple Dual Correlated Sampling algorithm to determine the signal as a subtraction from the baseline.

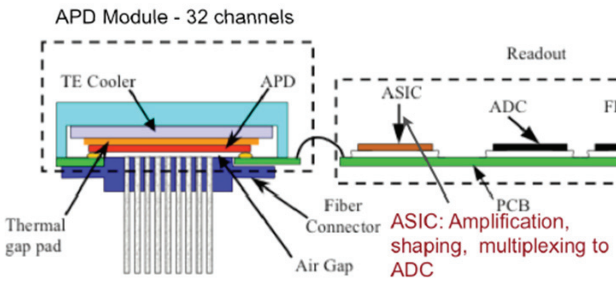


Fig. 8. Schematic view of a Front End Board.

For a minimum ionizing particle passing through the far end of a far detector cell, approximately 30 photoelectrons will be recorded resulting from 10-12 MeV energy deposited in the liquid scintillator. This light yield for the least sensitive (most attenuated) signal corresponds to a minimum signal to noise ratio of approximately 10:1.

### 3.3. Data Concentrator Module

A DCM[1] is a custom electronic component used to consolidate and concatenate the data from up to 64 FEBs; program, configure and monitor the FEBs; and pass the Timing System Clock and Sync command to the FEBs. As shown in Figure 9, the DCMs are attached to racks on the sides and top of the detector and


Fig. 9. Photo of the NDOS prototype detector highlighting a DCM, FEB, and Power Distribution Box (PDB).

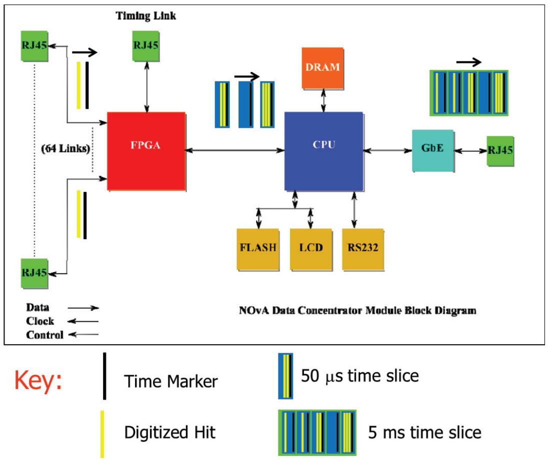


Fig. 10. Schematic of a DCM.

communicate with the FEBs through point-to-point serial data links with dedicated differential pair lines for Clock, Sync, Command, and Data.

Figure 10 shows a schematic block diagram of a DCM. The data flow in this diagram is left to right, beginning with the 64 FEB serial data link connections on the left. The FEB FPGA produces timing markers at periodic intervals (50 $\mu$s) interspersed with digitized hits. The digitized hits are consolidated by the DCM FPGA to 50 $\mu$s time slices containing data from all 64 FEBs. An application running on the DCM PowerPC CPU consolidates this data further to a longer time slice (5 ms) and routes this time slice to a downstream buffer node for further processing.

The routing of the 5 ms time slices of data by the DCM to a downstream Buffer Node in the Buffer Farm is done in round robin fashion such that each successive 5 ms time slice is sent to the next Buffer Node in the round robin chain. Data packets are transferred using TCP/IP and, if necessary, a time delay will be imposed on the time slices at the DCM before sending them to the downstream Buffer Node to mitigate traffic problems on the network. All DCMs throughout the detector send hit data corresponding to one 5 ms time slice to the same Buffer Node, so that one Buffer Node holds all hit data from throughout the detector for one 5 ms time period.

### *3.4. Buffer Node and Trigger*

A Buffer Node is a commodity server residing in a Buffer Farm of up to 140 Buffer Nodes. A schematic of the Buffer Node application is shown in Figure 11. The Buffer Node application receives data from all

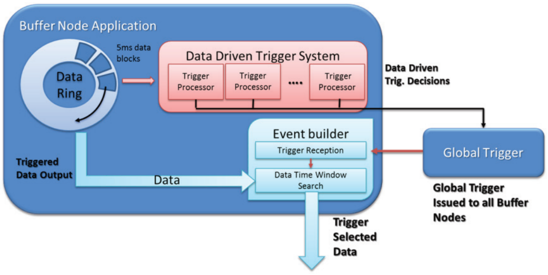


Fig. 11. Schematic of the Buffer Node application.

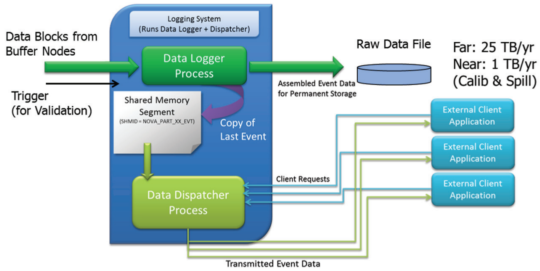


Fig. 12. Schematic of the Data Logger application.

DCMs throughout the detector corresponding to one 5 ms time slice, and buffers this data for a minimum of 20 s. An external Global Trigger system provides triggers to the Buffer Node in the form of a start time and time window, so that the Buffer Node application can select data corresponding to this time window from the buffered data. Only trigger selected data is written by the Buffer Node to the downstream Data Logger.

Triggers supplied by the Global Trigger to the Buffer Node include spill and calibration triggers, where the spill triggers are derived from a beam spill signal and the calibration triggers are intended to randomly sample the data. The Buffer Node application also provides support for Data Driven trigger algorithms to run on separate threads. These algorithms may examine the buffered data to look for data of spatial and temporal topological interest, for example one such algorithm will search for characteristics of neutrino events generated from a Supernova. If a Data Driven trigger determines something has occurred of interest, this trigger will be sent to the external Global Trigger application, where the Global Trigger can use a consensus of such signals from Buffer Nodes to issue a trigger globally to all Buffer Nodes. In this way, events which extend over more than a 5 ms time intervals can be triggered and read out over the entire detector.

### *3.5. Data Logger*

The Data Logger is a single commodity server and receives trigger-selected data from the Buffer Farm to format into an Event. A schematic of the Data Logger application is shown in Figure 12. A trigger issued to the Buffer Farm is also issued to the Data Logger application for validation purposes. The events created by the Data Logger are written to disk, where they are then archived to FNAL mass storage via a separate File Transfer system. The expected data sizes written to disk including only calibration and spill data are 25 TB/yr (FD) and 1 TB/yr (ND).

The Data Logger also writes Events to a shared memory segment, from which a Dispatcher application can serve the data to quasi-online external client applications such as Online Monitoring and Online Event Display.

### *3.6. Timing Distribution System*

All FEBs and DCMs throughout the DAQ system are synchronized to a common high precision 16 MHz clock reference. Clock signals are distributed to DCMs by Slave Timing Distribution Units (STDUs) daisy-chained along the backbone of the detector as shown in Figure 13. The Master Timing Distribution Unit

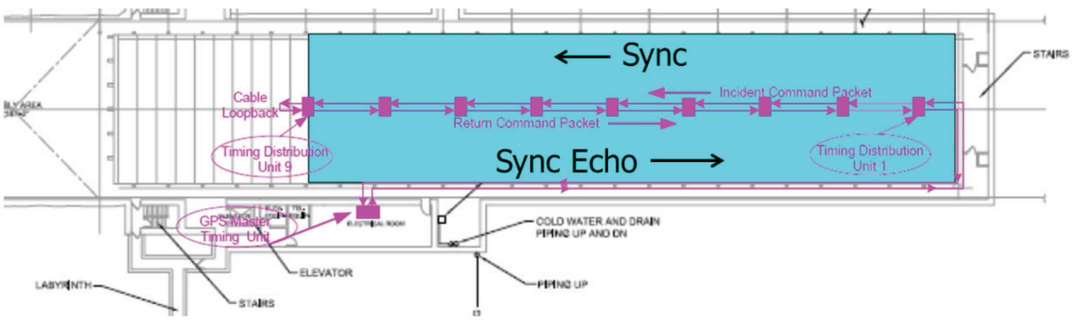


Fig. 13. Timing Distribution System

(MTDU) derives the clock signal from GPS and distributes the clock signal to the first STDU in the chain. Each STDU regenerates the signal before sending it to the next STDU in the chain and also transmits the clock signal to two groups of 6 daisy-chained DCMs along the top and side of the detector.

Each TDU has 4 differential pair lines for communication: Sync, Command, Clock and Sync Echo. The Sync Echo line is used to implement a "Delay Learn" feature of the STDUs to compensate for cable length propagation delays using a TOF/2 method. As shown in Figure 13, when a Sync command reaches the last STDU in the timing system chain, a cable loopback feeds the Sync command into the Sync Echo input, such that the Sync Echo will then be propagated up the timing chain. On start-up, the STDUs are placed in "Learn" mode and a Sync is issued by the MTDU. On the receipt of a Sync when in Learn mode, the STDU will start a timer which will run until it receives a Sync Echo. This time interval is recorded by the STDU and can be used to self correct for propagation delays for future synchronization commands issued by the MTDU to within +/- 1/2 clock cycle.

### *3.7. Control and Monitoring*

In addition to those components involved in data flow and timing, the DAQ system consists of several additional components for control and monitoring purposes, a few of which are discussed here.

The Run Control system provides overall control of the DAQ system. All DAQ components implement a well-defined state model and, under the command of Run Control, make transitions between states in that state model. Run Control is implemented using a client/server framework and is written in C++ using Qt tools to implement the Graphical User Interface.

The DAQ Monitor system is used to monitor the health and performance of the DAQ system. It uses the Ganglia Monitoring System[5] at its base, enhanced for NO$\nu$A purposes with client application interface classes for submitting custom metrics and a customized version of the Ganglia web display. Metrics are stored in a database for long-term diagnosis and study of DAQ performance. Every node in the system is monitored by the DAQ Monitor, including the DCM nodes.

The Message Passing System handles control and status messages sent from one DAQ component to another using a publish/subscribe methodology. It uses OpenSplice DDS[6] from Prism Tech at its base, customized with NO$\nu$A specific layers to provide ease-of-use.

The Message Facility system is used for logging messages and is based on the CMS message logger[7]. The Message Facility is capable of logging messages to multiple destinations including standard ouput, file and/or a Message Server. The Message Server is equipped with a GUI display for viewing messages and includes capability for server-side filtering of messages.

## 4. NDOS Performance

The NDOS prototype detector has proved to be a valuable test bed for commissioning all aspects of the detector construction and operation including the DAQ system. The DAQ system has been deployed successfully to collect both beam and cosmic data. An example of a neutrino event recorded by the DAQ

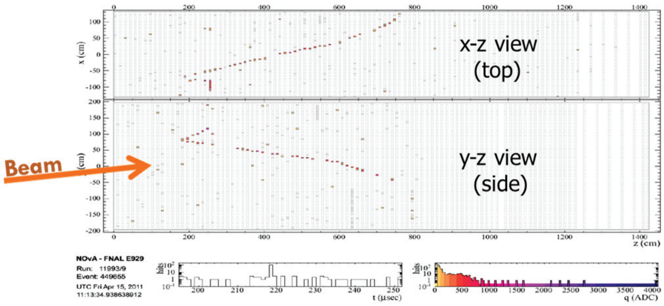


Fig. 14. A candidate quasielastic $\nu_\mu$ event observed in the NDOS detector. An approximation to the direction of the beam in the y-z view is shown to guide the eye.

is shown in Figure 14 and both NuMI beam neutrino events and Booster beam neutrino events have been identified and correlated with the beam time and direction as shown in Figure 15, indicating the DAQ system

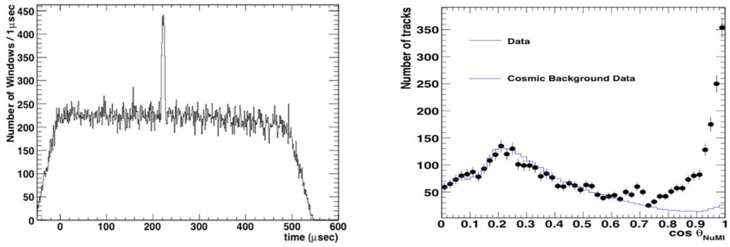


Fig. 15. The NDOS timing distribution on the left shows a peak corresponding to the expected arrival time of NuMI beam neutrino events. The distribution on the right shows the angular distribution of reconstructed tracks measured relative to the NuMI beam direction. The in-spill data exhibits a strong peak in the beam direction over the cosmic ray background.

is performing as expected.

Many performance gains and bug fixes have been made as a result of commissioning NDOS, including more than a factor of two gain in data throughput since its initial deployment to NDOS.

## 5. Summary and Outlook

The NO$\nu$A DAQ system has been designed and its core functionality has been implemented and deployed to the NO$\nu$A prototype detector (NDOS) successfully. The effort of the DAQ group is now focused on enhancements required for deployment at the FD. These enhancements include automatic error recovery, scaling GUIs/Displays for the larger number of nodes at the FD, and partition support for operating different sections of the detector in different run modes. It is expected that the first data from the FD will be read out in early 2012.

## References

[1] D. Ayres, et al., NOvA Technical Design Report, Tech. Rep. Fermilab-Design-2007-01, Fermilab (2007).
[2] S. Phan-Budd, Construction of PVC Extrusions for NOvA Near and Far Detectors, in: Technology and Implementation in Particle Physics 2011 (these proceedings), 2011.
[3] A. Smith, The NOvA Module Factory Quality Assurance System, in: Technology and Implementation in Particle Physics 2011 (these proceedings), 2011.
[4] M. Muether, Initial Performance from the NOvA Surface Prototype Detector, in: Technology and Implementation in Particle Physics 2011 (these proceedings), 2011.
[5] Ganglia Distributed Monitoring System, http://ganglia.sourceforge.net.
[6] OpenSplice DDS from Prism Tech, http://www.prismtech.com/opensplice.
[7] CMS MessageLogger, https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideMessageLogger.