

The NO ν A Data Acquisition System

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Abstract. The NO ν A experiment is a long baseline neutrino experiment designed to make key measures to determine the neutrino mass hierarchy, neutrino mixing and CP violation in the neutrino sector. In order to make these measurements the NO ν A collaboration has designed a highly distributed, synchronized, continuous digitization and readout system that is able to acquire and correlate data from the Fermilab accelerator complex, the NO ν A near detector at Fermilab and the NO ν A far detector which is located 810 km away at Ash River, MN. This system has unique properties that let it fully exploit the physics capabilities of the NO ν A detector. This paper discusses the design of the NO ν A DAQ system and its capabilities.

1. Introduction

Recent measurements of the neutrino mixing angle θ_{13} have greatly changed the landscape of measurements that the NO ν A experiment can make. The relatively large value of θ_{13} estimated from recent global fits at $\sin^2 2\theta_{13} \approx 0.090$, mean that the oscillation signatures the NO ν A far detector will see over the course of its first 6 year run will be significant and will allow the experiment to place strong limits on the neutrino mass order and the CP violating phase δ_{CP} of the PMNS mixing matrix.

The NO ν A experiment is long baseline experiment designed to measure the oscillation probabilities $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. From the standard theory of neutrino flavor oscillations through matter, it is possible to derive allowed contours for the neutrino/anti-neutrino oscillation probabilities as a parametric function of the phase δ_{CP} . When this is done, the ambiguity in the sign of the mass splitting between the first and the third neutrino mass states (Δm_{31}^2) leads to two possible elliptical contours. One contour corresponds to the normal mass hierarchy where the first neutrino mass state which couples most to the electron, is the lightest. The other contour corresponds to the inverted hierarchy where the ν_3 eigenstate is the lightest. The NO ν A experiment's measurements of the oscillation probabilities can then be plotted on these curves along with the projected 1σ and 2σ contours for the measurements. The plot in Fig. 1 shows one such example, where if NO ν A were to measure the starred point, we would conclude that the inverted mass hierarchy is excluded at a 90% C.L. and that the CP violating phase was non-zero.

To perform these measurements, the NO ν A experiment has been designed as a two detector, long baseline experiment with a high intensity, narrow band neutrino beam. The NO ν A project formally consists of an upgrade to the Fermilab accelerator complex to double the power of NuMI (Neutrinos at the Main Injector) beam line to 700 kW at beam momentum of 120 GeV/c, and the building of two large liquid scintillator based neutrino detectors. The far detector for the NO ν A experiment is a 15 kT totally active (70% active) surface detector that is tuned for the

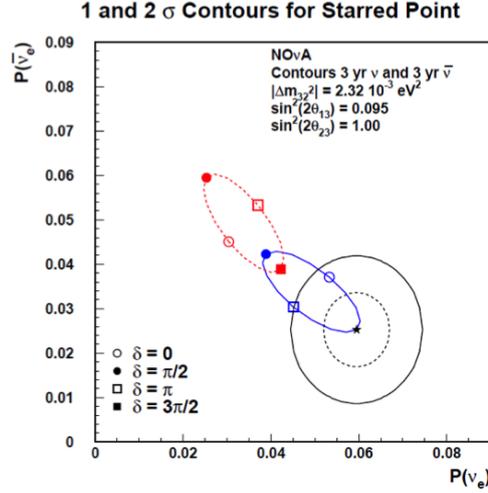


Figure 1. Bi-probability contours for the normal (blue) and inverted (red) neutrino mass hierarchies corresponding to the NO ν A experiment’s baseline and ν energy spectrum. An example test point is plotted at $\delta_{CP} = 3\pi/2$ with the corresponding NO ν A 1 and 2 σ sensitivities.

detection of neutrino interactions with an energy of 2GeV. The near detector shared an identical design as the far detector but is built to have a 1/4 scale cross section of the far detector and only 1/5 the total length.

Both detectors, shown in Fig. 3 have been optimized as highly segmented, low Z range stack/calorimeter and tuned to reconstruct EM showers as well as muon tracks in the 1-2GeV range (corresponding to ν_e charged current interactions and ν_μ quasi-elastic charged current interactions.) The detectors are also designed to be efficient for the detection of low energy interactions and are sensitive to nuclear recoils associated with ν interactions as well as Michel electrons resulting from muons which range out in the detector.

The far detector will be installed at the NO ν A laboratory in Ash River, MN. This site, depicted in Fig. 2 was chosen to be at a distance of 810 km from the NuMI production target and at an angle of 14 mrad off of the primary beam axis in order to tune the L/E of the baseline and beam to match the first oscillation maxima in the neutrino oscillation spectrum.

The physical size of the detectors, the high channel counts and high data rates that result from the detectors being on the surface with limited overburden, cause NO ν A to be a challenge for modern computing.

2. Core Measurements

In order to make the core $\nu_\mu \rightarrow \nu_{e,\mu}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{e,\mu}$ oscillation measurements the experiment needs to be able to send a narrow (10 μs pulsed beam of mainly ν^μ ’s to both the small near detector and the massive far detector. In each of these detectors the beam will interact and leave characteristic topologies corresponding to the different neutrino interaction modes. The experiment must then have an ability to correlate which interactions in the detectors corresponded with the actual beam pulse. Finally the experiment needs to be able to compare the rates of interaction in the near and far detectors along with their energy spectra to determine the rates at which the different neutrino flavor states are appearing/disappearing.

The difficulty in designing a data acquisition system that can perform these simple measurement objects, is that it is extremely difficult to perform the correlation of the beam



Figure 2. The NO ν A detector is located at a site in Ash River, MN which is 810 km from Fermilab at an angle of 14 mrad off of the primary NuMI beam axis. This puts the NO ν A detector at an L/E corresponding to the first oscillation maxima.

spill with the actual interactions in the detector. The reasons this is difficult for the NO ν A experiment design are three fold.

First because the detector is 810 km away from the primary production target, there is no way to provide a hard timing signal to the far detector site that can arrive fast enough to “trigger” the readout of the far detector. For this reason the readout needs to happen independent of any knowledge of the beam conditions and the data needs to be buffered long enough for any signals that are going to be sent to propagate to the far detector site.

The second reason that the correlation of the beam spill with the data is difficult is that there is also no way to definitively predict when a beam spill will occur due to the dynamic nature of the Fermilab beam systems. This makes schemes where the detector is pre-triggered or predictively triggered based on the last known beam spill highly inefficient and can cause loss of data if the prediction is off by even a few microseconds. While the NuMI spills are slotted into the each accelerator super cycle at well defined points, the actual timeline structure changes based on which experiments and beam line are actually running. Additionally the absolute alignment of the start of the super cycle with respect to the current “wall” time will also vary based on the timelines. It is also difficult to verify that a spill has actually happened until after it has occurred and the beam line monitors have measured the flux of protons that were extracted onto the target.

The other difficulty in performing the NO ν A triggering/beam correlation is that as a surface detector there is always a significant amount of activity in the detector coming from cosmic rays. This makes simple “activity” based triggers extremely difficult since without the fine timing information of the beam spill window, most neutrino interactions will be lost in the sea of cosmic rays that are streaming through the detector.

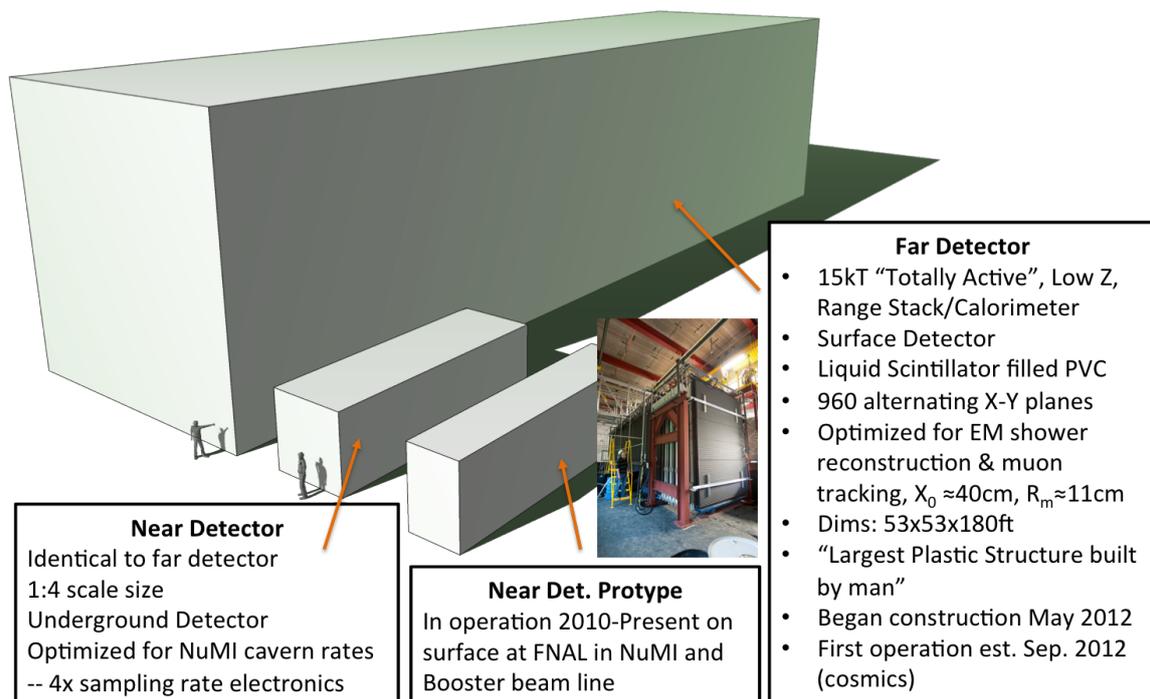


Figure 3. The $\text{NO}\nu\text{A}$ experiment will build a total of three separate detectors. The far detector is the largest at a total mass of 15 kT, while the smallest is the near detector prototype which was built in 2010 and operated from the fall of 2010 through May 1, 2012 in the NuMI and Booster neutrino lines at Fermilab.

As a result of the difficulties outlined above, the $\text{NO}\nu\text{A}$ data acquisition system chose to design a system that would not require a tradition trigger to initiate the readout of the front end electronics, while at the same time would be able to tolerate extremely long latencies in the propagation of information about the beam spills to the Ash River site.

The $\text{NO}\nu\text{A}$ solution was to use a continuous readout system in conjunction with an absolute time synchronization of all the readout electronics. In this scheme:

- (i) Every channel of readout is instrumented with a TDC in the form of a high resolution time stamp counter.
- (ii) Every channel in the detector is synchronized to every other channel in the detector such that their time stamp counter increment in unison.
- (iii) Every time stamp counter is additionally synchronized to an external "wall" clock such that the value held in the time stamp counter corresponds to the actual wall time.

Then the detector is put in a free running, continuous readout mode. In this mode all the hits that appear in the detector above a noise threshold receive a time stamp, are readout, sorted into continuous time windows and stored in a deep hit buffer.

In parallel to the continuous readout, when a beam spill occurs at Fermilab it is similarly time stamped with an identical high precision time stamp counter that is synchronized to an external "wall" clock. The spill information, including the high resolution time stamp is then transmitted to the far detector site.

When the beam spill information is received the hit buffers are searched for the any hit data that overlaps with the beam spill and the results are stored through a data logger system to permanent storage.

The advantage of this system is that it provides a true free running system where the electronics are always live and always digitizing. It also provides a readout that is completely deadtime-less. This means that the whole system becomes sensitive to interactions both from the beam but also from external sources such as cosmic rays, cosmic neutrinos or theorized exotic particles such as magnetic monopoles.

The draw back of this system is that it produces a flood of data that needs to be continuously buffered. In the case of the NO ν A detector the aggregated data rate produced by the front end boards can reach a sustained rate of 4.3 Gb/s which needs to be transferred over a modern switch fabric from the front end systems to a large farm of computers which serve as the buffers for the data while it awaits triggering. This requires that the network and computing resources that are used for the transfers and buffering be capable of handling these rates.

3. Readout Design

The NO ν A readout is hierarchical and arranged in a tree'd topology where at each level the data being readout is aggregated and sorted into discrete time slices. At the lowest level in this tree are the 368,000 detector readout cells.

The NO ν A detector cell, shown in Fig. 4 is a 15.6 m long, skinny tube filled with of liquid scintillator, with a wave shifting fiber looped down the length of the cells. When a particle crosses the cell, the light from the scintillator is collected by a wave shifting fiber which is looped down the length of the cell with both ends of the fiber being readout by a single pixel of an avalanche photo diode (APD).

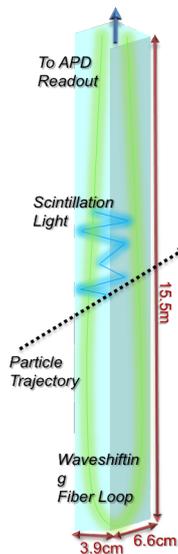


Figure 4. The NO ν A readout cell is a 15 m long tube of liquid scintillator formed by the walls of a ridged PVC extrusion. The cell is readout at one end by a wave shifting fiber and an avalanche photo diode which collect a measured light output of 30-38 p.e. from the far end of the cell.

The signal from the APD is amplified and shaped by a custom ASIC to produce a waveform shown in Fig. 5 which is designed to have a 380 ns rise time and 7 ms fall time. These choices of rise and fall times are optimizations based leakage current and shot noise of the APDs and front end boards and minimize the effects of noise on the readout in order to obtain a minimum signal to noise ratio of 10:1 for signals coming from the far end of the detector cells. The waveforms

from the detector cells are sampled by a high speed ADC at a 2 MHz sampling frequency to obtain multiple sample points along the baseline, rising edge and falling tail of the waveforms. A dual correlated sampling algorithm is then used to establish a rising edge triggered threshold under which the sampling points are zero suppressed. This threshold is set independently for each channel of the detector, but for the uncooled APDs that were used for the prototype near detector during the 2010-2012 run period, these thresholds average approximately 35 ADC counts over the baseline, corresponding to a detection threshold of approximately 0.5 MIP.

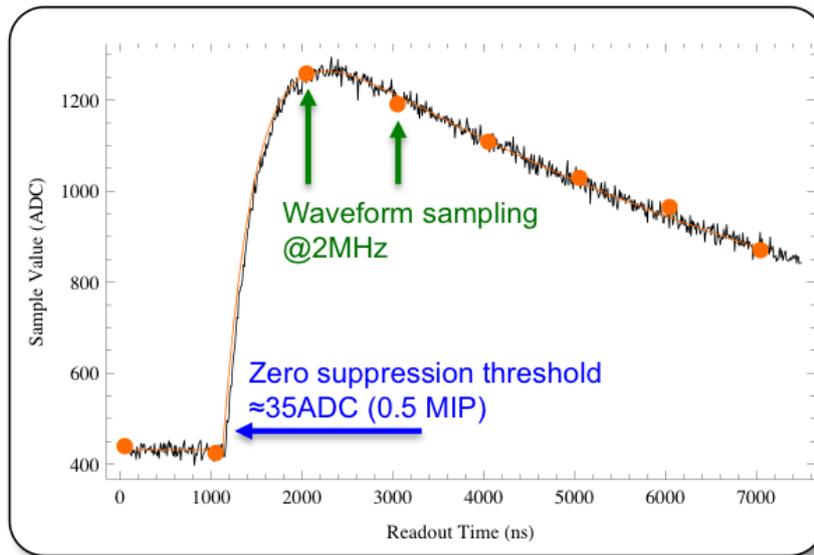


Figure 5. The signal from the APD is amplified and shaped by a custom ASIC on the front end board to produce a well defined waveform that is then sampled with a 2 MHz digitization clock. A dual correlated sampling algorithm is used to establish a threshold for zero suppression of the data at the level of 35 ADC counts above the baseline.

The data streams the front end boards are sent to a data concentrator module (DCM) which aggregates and sorts the data. The DCM is a custom built single board computer based off of a PowerPC 8347 platform. The DCM takes input data streams from up to 64 front end boards from a localized geographic region of the detector, as shown in Fig. 6 and time orders them into windows corresponding to 50 μs intervals. The DCM organizes this data inside of a large Xilinx FPGA. When the data has been successfully organized into a 50 μs “microslice” an interrupt is generated on the PowerPC. This causes a custom Linux kernel module to read the data out of the FPGA via a DMA copy into the normal system memory of the PowerPC platform. The data is then further organized by event building software that runs on the embedded linux system. The DCM event builder constructs larger 5 ms “millislices” which are optimized for network transmission under a 9000 mtu jumbo frame ethernet packet. The DCMs operating in this mode have been shown to be able to handle a sustained data rate of 24 MB/s, where the limitation on the data rate comes primarily from the speed of the memory bus on the 8347 platform.

The readout regions defined by the DCMs are synchronized through the use of a sophisticated timing system. This system provides a stable master clock line as well as command and SYNC lines that permit the time stamp counters that are present on the front end boards, DCMs and the timing system to be loaded and synchronized with a universal “wall time” based off of a link to the global positioning system (GPS). The timing system, shown schematically in Fig. 7 is capable of operating at 16/32/64 MHz and can achieve unit to unit synchronization that

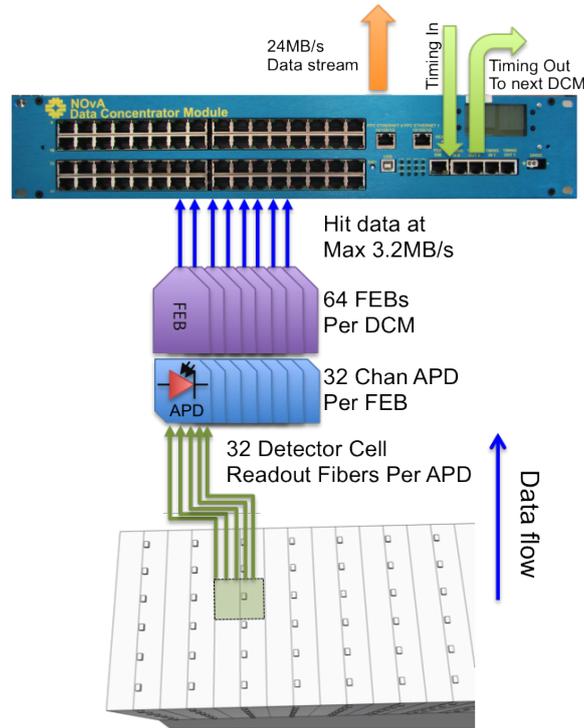


Figure 6. The DCMs aggregate data from 2048 channels of a localized readout region of the detector and produce a 24 MB/s output data stream that is transmitted to a large computing farm over standard gigabit Ethernet.

is accurate to within one clock cycle. This system is also used to time stamp the beam spill information coming from the Fermilab accelerator complex. The time stamps that the timing system produces are universal wall times expressed in the 64 MHz NO ν A time specification. This makes the data that is taken by the detector and the beam spills that are produced by the accelerator easy to correlate.

Through these systems the DAQ is able to synchronize and readout 368,640 far detector readout cells spread over 11520 different front end boards. The system has been shown to work with the prototype near detector at Fermilab and the synchronization ability of the timing system was verified by looking at the time variation of muon tracks in the detector as they cross readout/synchronization boundary. Figure 8 shows an example of this type of synchronization for a ν_{μ} quasi-elastic interaction whose muon crosses a readout boundary in both the X-view and Y-view.

Once the data streams are built by the DCMs, all the data from a specific time window is transmitted to a large computing cluster that is housed at the far detector site. Each DCM has a list of available “buffer nodes” within the computing cluster to which it can send data. The DCMs send the data from each 5 ms millisecond that is acquired to the list of buffer nodes in a specific “round robin” pattern. All of the DCMs use the same pattern so that all the data from across all of the geographic regions of the detector from a given 5 ms time interval sent to the same buffer. This gives each buffer node a complete snapshot of the detector.

When the round robin pattern is complete the DCMs cycle back to the first buffer node in the sequence. For the nominal far detector cluster size of 200 buffer node computers, this cycle repeats once every second. It should be noted though that when the buffer node receives

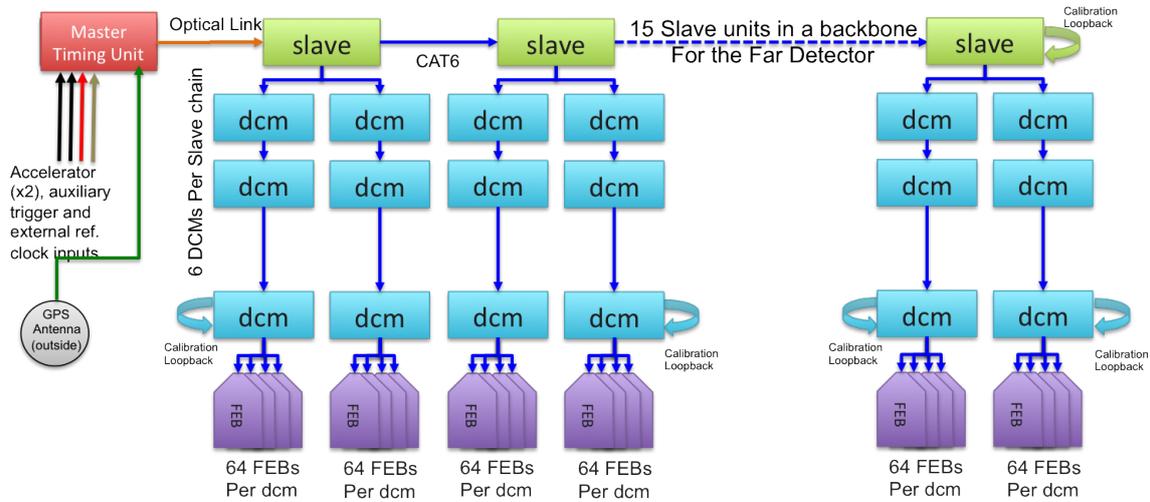


Figure 7. Schematic representation of the NOνA timing and synchronization system.

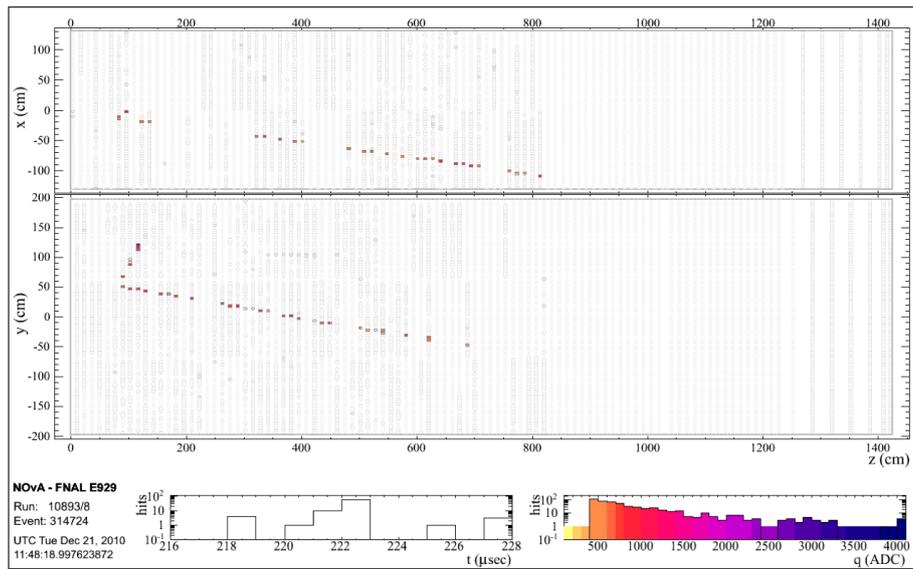


Figure 8. Example of validation of timing system synchronization across readout boundaries through the examination of muon tracks in X and Y detector views.

a new set of milliseconds the older ones are not immediately discarded, rather a circular buffer with a fixed event depth is maintained and events in it are not discarded until the buffer is full. In the original baseline designs the depth of the circular buffers for the buffer nodes were set to allow for a system wide buffering of 20 s worth of data. Advances the cost and size of commodity random access memory permit us (with the hardware that has been purchased and installed at the Ash River computing center) to buffer an estimated 69 minutes of raw data in the RAM of the buffer nodes. This capability opens up the possibility to perform extremely high latency trigger decisions, such as would be required if a supernova were detected by an external observer and there was a need to extract the corresponding time interval from the

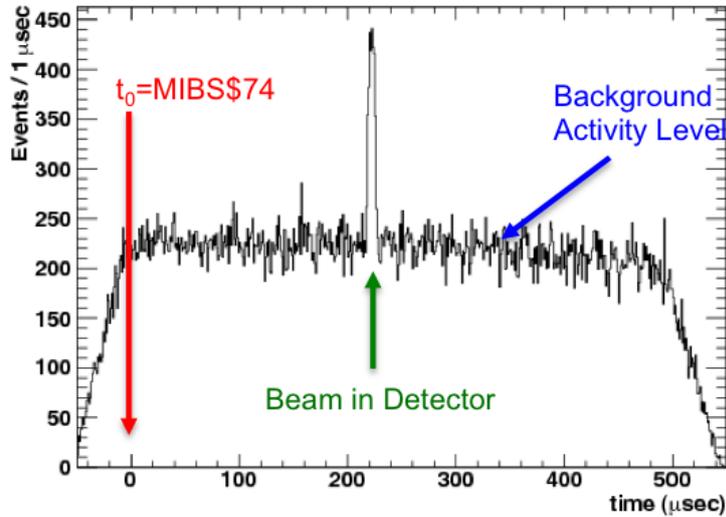


Figure 9. NuMI beam peak derived from the prototype near detector during 2011. The beam induced activity is clearly identifiable above the normal background levels.

buffered NO ν A data.

4. Triggering

In order to perform measurements related to the core neutrino oscillation topics ($\theta_{13}, \theta_{23}, \delta_{CP}$ and Δm_{31}^2) the only triggers that are required are the NuMI beam spill information and a calibration pulser. These triggers impose selection criteria that are essentially zero bias. The beam trigger required only that a beam spill occurred at Fermilab, and it selects a time window centered around the time of the beam spill that covers both the 10 μs spill as well as side bands on each side of the spill to allow for a determination of background rates. In the case of the prototype near detector a 500 μs window was selected in order to allow the experiment to locate and characterize the NuMI beam at the location of the prototype detector. This distribution is shown in Fig. 9, where the beam peak is clearly identifiable above the level of background activity in the detector.

For the production running of the far detector the side bands that are acquired along with the beam spill are reduced to 30 μs and additional “off spill” time windows are taken for calibration purposes.

It is however important to note that all of the data from the detector ($\approx 4.3Gb/s$) is buffered in the computing farm, while only 30 μs of each 2s is written out to the final data stream as physics beam triggers. Being able to examine the full data stream in real time, while it is in the buffer nodes, gives us the opportunity to generate “data driven triggers” which can examine the topologies in the data stream and make selections that would otherwise not be possible under the minimum bias readout scheme. Because the NO ν A detector is 100% live, these triggers have tremendous potential for accessing non-accelerator based physics and calibration sources. They provide an opportunity to improve detector calibrations using high energy “horizontal” muons which pass down the the detector axis. They provide the ability to verify the detector/beam timing offset by independently identifying contained neutrino events in the detector. They allow for searches for exotic phenomena in non-beam data such as magnetic monopoles and WIMP annihilation signatures. They also permit the search for upwards going and directional sources

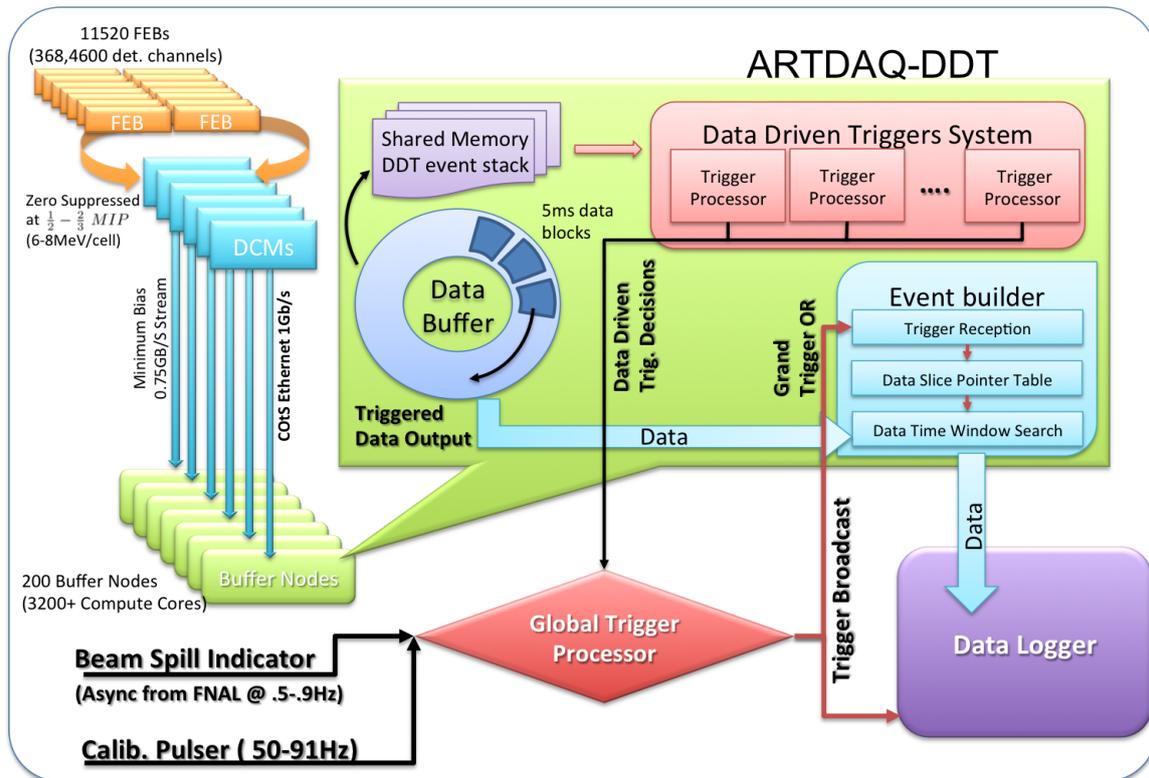


Figure 10. The NOνA DAQ readout system with inclusion of a data driven triggering system. Data is shared between the primary data buffer and the ARTDAQ analysis framework through a shared memory segment that is populated by the event builder and read by the data driven trigger system.

of cosmic neutrinos, and event have the potential to detect the neutrino flash from nearby supernovae.

The NOνA DAQ system has been modified with prototype versions of a data driven trigger system based on the ART analysis framework. The trigger system is activated directly on the buffer nodes and shares the raw hit data with the event building process through a shared memory segment. This architecture allows for the triggering system and event building systems to be separate from each other and insulated incase of non-standard flow during data analysis. This architecture also permits the data driven trigger system to take advantage of the multiple processing cores on each buffer node to achieve a high degree of parallelism in the analysis. A schematic overview of the NOνA DAQ system with the integrated data driven trigger (ARTDAQ-DDT) is shown in Fig. 10.

The NOVA-DDT prototype system has been tested using a real world track finding algorithm based on a 2D hough transform for each of the detector views. This transform technique was chosen since it was an example that would permit examination of the scaling of the trigger system under an N^2 complexity algorithm, but also allow for exploitation of the parallelism that is possible with both the multi-core CPUs that the buffer nodes have and the benefits outfitting the buffer nodes with massively parallel GPUs would afford. The NOVA-DDT-HOUGH trigger was operated on 5 ms time windows from the prototype near detector with zero suppression thresholds set to mimic the data rates of the far detector. The total channel count readout was approximately 1/30 of the full far detector readout. The slices of data were sorted according to

detector view and each view was processed as a single block time block. The goal from the tests were to achieve a transformation and trigger decision within 60 ms, corresponding to the round robin period of the small 12 buffer node test cluster which the near detector prototype uses for readout.

In these tests the system was able to achieve a decision in on average 98 ms. Only 2% of the processing time was spent in the overhead that is induced by the ARTDAQ framework, the rest was spend within the data unpacking and computation loops of the transform algorithm. It is however important to note that the test utilized only 1/16th of the available CPU resources on the buffer node machines and did not exploit any of parallelization of the algorithm or partitioning of the data which are known to greatly improve the performance of this type of Hough transform. Figures 11 and 12 show the results of these tests a the distributions of the time to decision and the framework overhead percentage for the system.

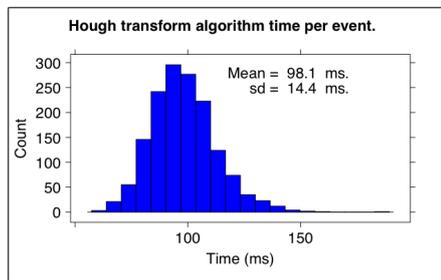


Figure 11. Time to decision for the NOVA-DDT-HOUGH trigger as run on the NO ν A prototype detector cluster.

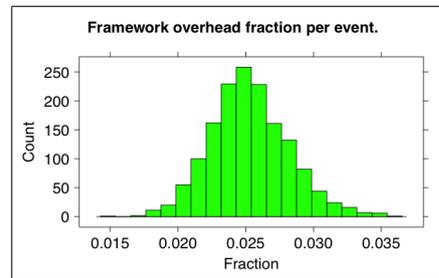


Figure 12. Framework overhead as a fraction of total processing time for the NOVA-DDT-HOUGH trigger

5. Conclusions

The NO ν A experiment has designed and implemented a robust set of DAQ and readout systems which are capable of meeting the requirements imposed by the core nova neutrino measurements. The system has solved the problem of performing site to site correlation of beam and detector data, as well as designing a method for synchronizing over 368000 channels of readout to high precision.

The challenges being faced by the NO ν A DAQ are now the production deployment of the system on the 15 kt far detector and its ability to scale with both the channel counts and readout rates that will be encounter there. The experiment is also exploring the power and opportunities that data driven triggering will afford the experiment both in terms of improved calibration methods and in opportunities to access physics outside the original scope of the NO ν A Experiment.