**5 OVERVIEW OF THE NOνA DESIGN ........ 5-2**

5.1 INTRODUCTION ........ 5-2
5.2 THE NEUTRINO BEAM ........ 5-2
*5.2.1 Recycler Upgrades ........ 5-2*
*5.2.2 Main Injector Upgrades ........ 5-3*
*5.2.3 NuMI Beamline Upgrades ........ 5-3*
5.3 THE FAR DETECTOR SITE AND DETECTOR HALL AT ASH RIVER, MINNESOTA ........ 5-3
*5.3.1 The Far Detector Site ........ 5-3*
*5.3.2 Cooperative Agreement ........ 5-4*
*5.3.3 Environmental Assessment ........ 5-5*
*5.3.4 NOνA Far Detector Hall at Ash River ........ 5-5*
5.4 NEAR DETECTOR SITE AND DETECTOR AREA AT FERMILAB ........ 5-8
5.5 DESCRIPTION OF THE NOνA DETECTORS ........ 5-9
*5.5.1 The Basic NOνA Detector Element ........ 5-9*
*5.5.2 Liquid Scintillator ........ 5-10*
*5.5.3 Wavelength-shifting Fiber ........ 5-10*
*5.5.4 Rigid PVC Extrusions ........ 5-10*
*5.5.5 Extrusion Modules ........ 5-11*
*5.5.6 Photodetector and Electronics ........ 5-13*
*5.5.7 Data Acquisition System ........ 5-13*
5.6 ASSEMBLY OF NOνA DETECTORS ........ 5-13
*5.6.1 Integration Prototype Near Detector ........ 5-15*
*5.6.2 Near Detector ........ 5-17*
*5.6.3 Far Detector. ........ 5-17*
5.7 SUMMARY OF DESIGN CHANGES SINCE THE CONCEPTUAL DESIGN REPORTS ........ 5-20
*5.7.1 Major Changes ........ 5-20*
*5.7.2 Accelerator and NuMI Upgrades ........ 5-20*
*5.7.3 Site and Buildings ........ 5-20*
*5.7.4 Scintillator ........ 5-21*
*5.7.5 Fiber ........ 5-21*
*5.7.6 PVC Extrusions ........ 5-21*
*5.7.7 Extrusion Modules ........ 5-21*
*5.7.8 Electronics and DAQ ........ 5-22*
*5.7.9 Near Detector Site and Assembly ........ 5-22*
*5.7.10 Far Detector ........ 5-22*
5.8 VALUE ENGINEERING CONTINUES ........ 5-22
5.9 CHAPTER 5 REFERENCES ........ 5-22

# 5 Overview of the NOνA Design

## 5.1 Introduction

This chapter contains an overview of the NOνA technical design. More detailed descriptions of the design are presented in Chapters 8 through 17.

## 5.2 The Neutrino Beam

Figure 5.1 shows the Fermilab accelerator complex and proton source for NOνA. The accelerator and NuMI upgrades for NOνA will provide about a factor of two increased beam power relative to the current output. This is accomplished by reconfiguring the Recycler into a proton storage device and by increasing the acceleration rate and repetition rate of the Main Injector (MI). The increased beam power only requires a 10% increase in the total beam intensity in the MI. Shielding and cooling modifications to the proton source and upgrades in the NuMI neutrino line are also required to handle the higher beam power. Many existing components in the accelerator complex are reconfigured for the NOνA upgrade and additional new components are required. Details on the NOνA accelerator and NuMI upgrades are found in Chapter 8.

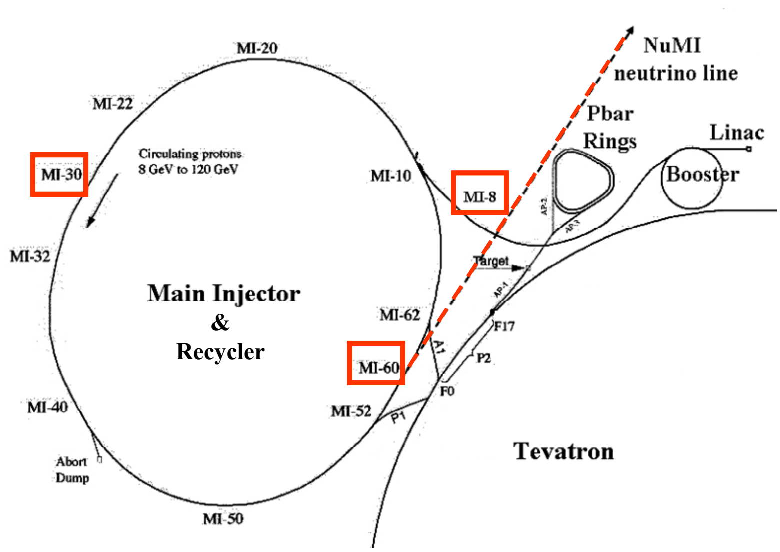



Fig. 5.1: Plan view layout of the Fermilab proton source consisting of the Linac, Booster, Recycler, Main Injector and NuMI neutrino line. The Recycler and Main Injector are in the same tunnel.

### *5.2.1 Recycler Upgrades*

The Recycler is a permanent magnet machine designed for 8 GeV beam transport in the MI tunnel and currently serves as the main anti-proton storage ring for the Tevatron Collider program. When Tevatron Collider operations cease, the Recycler will be used as a proton pre-injector for the Main Injector (MI) for NOνA. The Recycler is the same size as the MI and is located in the same tunnel, making it possible to do a single turn fill which minimizes the proton injection time in the MI cycle and maximizes the protons on target. Figure 5.1 shows the layout of the Recycler, MI and NuMI beamline.

To convert from an anti-proton storage ring to a proton pre-injector, anti-proton specific devices will be removed from the Recycler. A new proton injection line will be built connecting MI-8 (from the Booster) into the Recycler, and a new extraction line from the Recycler to the MI will be built at MI-30. Figure 5.1 indicates the MI-8, MI-30 and MI-60 locations around the

Main Injector / Recycler tunnel. These beamlines and the abort system will require five new kicker systems. A new 53 MHz RF system is required using two new RF cavities with controls and power installed in the MI-60 service building. The Recycler instrumentation will be upgraded with new beam position monitors, new intensity measuring devices, and new dampers.

### *5.2.2 Main Injector Upgrades*

For NOνA the Main Injector will be accelerating only 10% more proton intensity, but the beam power out of the MI will be much larger because the MI cycle time will be reduced from 2.2 seconds to 1.33 seconds. By using the Recycler Ring for stacking, the Main Injector cycle time is reduced to 1.5 seconds. To further decrease the Main Injector cycle to 1.33 seconds, the maximum acceleration rate must be increased from 204 GeV/sec to 240 GeV/sec. This faster ramp requires an upgrade to one of the quad power supplies. The MI also requires two extra RF stations to complement the existing 18 stations.

### *5.2.3 NuMI Beamline Upgrades*

As part of NOνA, the target and focusing Horn 2 locations will be changed to the medium energy configuration described in Chapter 2. A new medium energy target is required. The second horn must move to a new location within the target chase area and horn stripline extension is needed to reach this position. Other parts of the NuMI beamline upgrade are mainly cooling modifications to handle the increase in beam power from 400 kW to 700 kW and power supply upgrades to allow operations at the faster cycle time.

## 5.3 The Far Detector Site and Detector Hall at Ash River, Minnesota

### *5.3.1 The Far Detector Site*

The NOνA Far Detector will be located near Ash River, Minnesota. The site is 810.5 kilometers from Fermilab as shown in Figure 5.2. The Ash River site has the unique property of being the furthest site from Fermilab that is inside the United States and accessible by road.

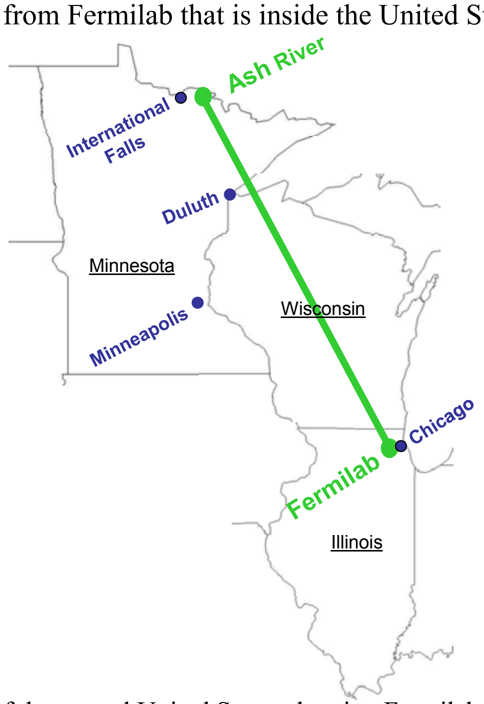



Fig 5.2: Map of the central United States showing Fermilab, the NuMI beamline, and the NOνA Far Detector site at Ash River, Minnesota.

The Ash River area is located about 40 km southeast of International Falls, Minnesota on the Ash River Trail (St. Louis County Highway 129) near the entrance to Voyageurs National Park as shown in Figure 5.3. Ash River is about an hour drive from International Falls, about a 3 hour drive from Duluth, and about a 5 hour drive from Minneapolis.

The site is 11.8 kilometers west of the NuMI beamline. The on-axis NuMI beamline is itself about 4.2 kilometers above the surface at 810 km from Fermilab. The site is 15 km east of U.S. Highway 53 along the Ash River Trail road (St. Louis County 129). Both U.S. 53 and County 129 are maintained year-round.

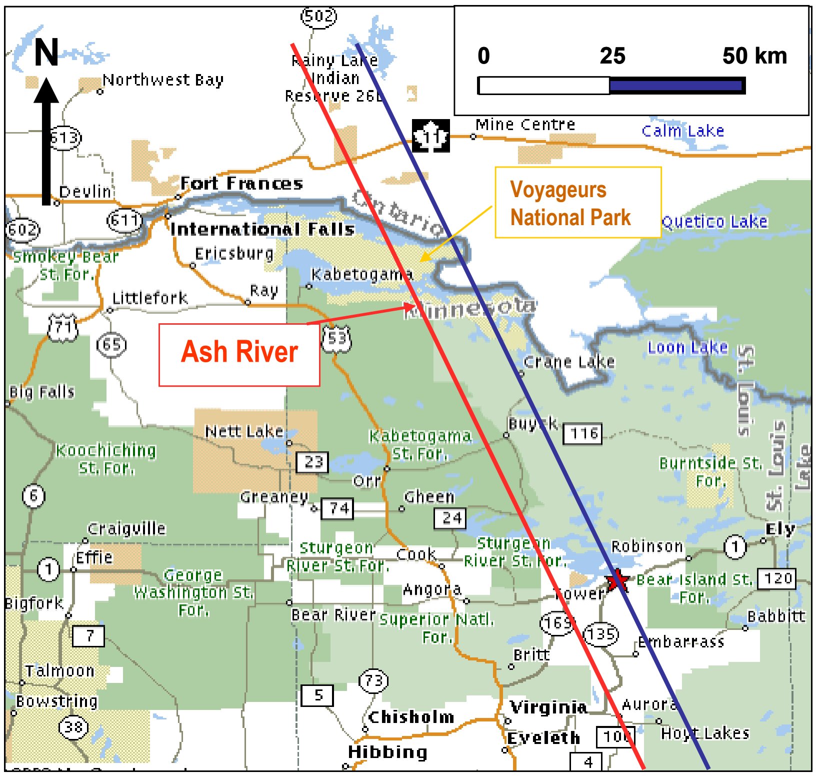



Fig. 5.3: Map showing the Far Detector site at Ash River. The NuMI beam centerline (blue) passes through the MINOS detector underground at Soudan (red star). The NOνA Ash River site is on the red line to the left (west) of the NuMI beam centerline, ~11.8 km (14.6 mradians) off-axis. Voyageurs National Park and the US-Canada border are just north of the site.

### *5.3.2 Cooperative Agreement*

The University of Minnesota has been selected by the Department of Energy as the recipient of a Cooperative Agreement [1] to build and operate the NOνA Far Detector building and access road in collaboration with the NOνA Project headquartered at Fermilab. Details of the collaborative agreement among the DOE, Fermilab NOνA Project and the University of Minnesota are in the NOνA Project Management Plan [2].

The Ash River site is a 50 acre plot that will be acquired by the University of Minnesota. A detailed local topographic map of the site is shown in Figure 5.4. The NOνA site is located about 1.5 miles south of an entrance to Voyageur's National Park. but is not visible from the park due to intervening hills and trees.

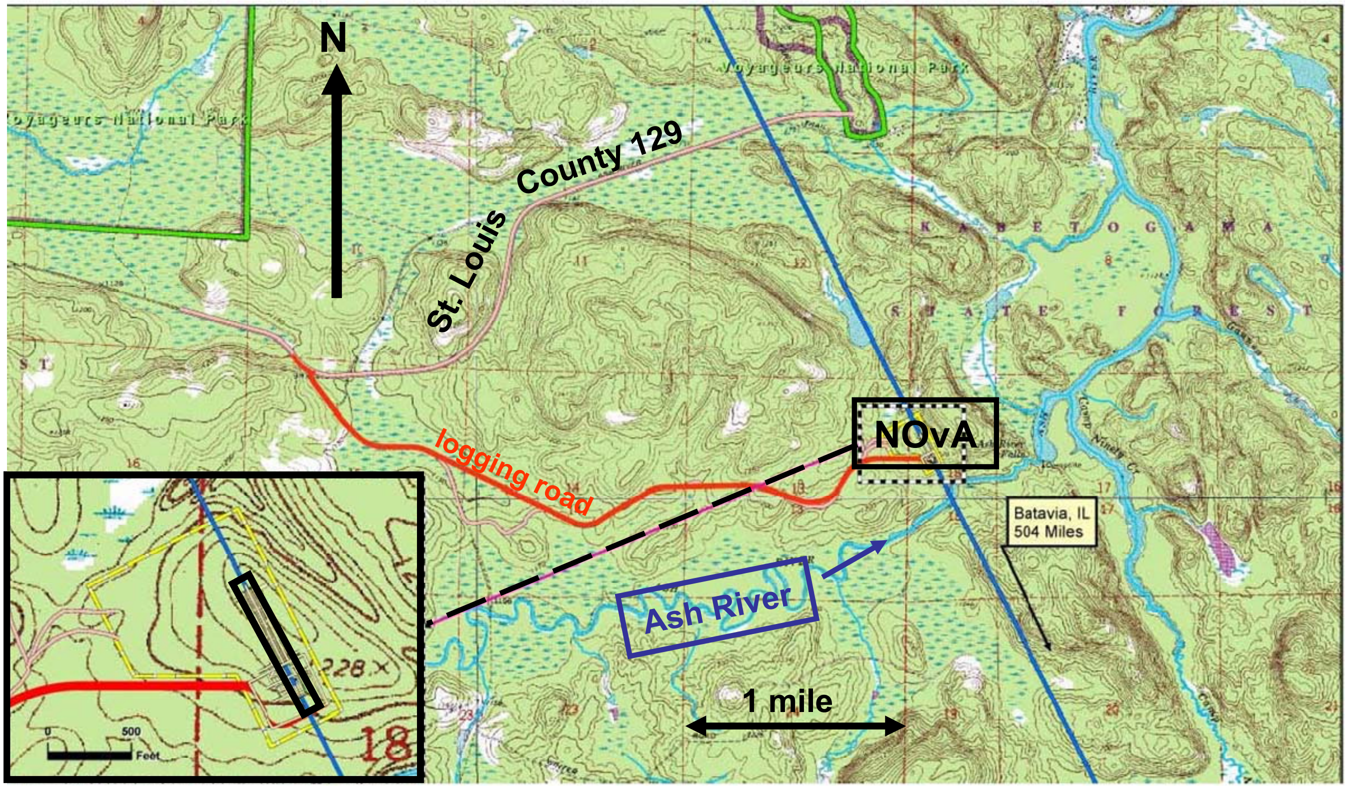



Fig. 5.4: Topographic map of the Ash River area. The NOνA site is in the rectangle at the end of the logging road (red) off St. Louis County Road 129. The inset in the lower left corner shows the site in more detail with the NOνA building sitting near the top of a hill at an altitude 1228 feet above sea level. The entrance road to the Ash River Visitor's Center in Voyageurs National Park is shown at the top right center of the map.

Access to the site is currently via an old clay base logging road off St. Louis County 129. The University of Minnesota will acquire an easement for this 3.6 mile long, 40 acre access road corridor. The access road passes through a wetlands area just as it leaves St. Louis County 129, and an Army Corps of Engineers permit will be required to allow construction of an all weather road like St. Louis County 129 to replace the existing logging road. A draft wetlands permit application has been prepared [3]. An advanced technical design of the access road is presented in Chapter 9.

### *5.3.3 Environmental Assessment*

A NOνA Environmental Assessment (EA) [4] has been written which treats the environmental issues in detail. The Ash River portion of the NOνA EA depends on a State of Minnesota process in which an Environmental Assessment Worksheet (EAW) [5] has been submitted for review by the University of Minnesota.

### *5.3.4 NOνA Far Detector Hall at Ash River*

The detector laboratory location at Ash River is in Section 18 of Township 68 North, Range 19 West, St. Louis County MN. This location is described in Table 5.1 and shown in Fig. 5.4. The site is located at an altitude of 1220 feet above sea level and is about 70 feet above the Ash River located to the south. Core borings at the site have determined [6] that the site has 5 – 15 feet of soil overburden and then is solid hard granite to a depth of at least 60 feet.

| Description | Latitude | Longitude | Distance from Fermilab (km) | Transverse distance from the NuMI beamline (km) | Altitude (ft) | Angle to the NuMI beamline (mradians) |
|---|---|---|---|---|---|---|
| This calculation is for the center of the detector based on GPS data for the corners of the detector building. | 48.37912 | -92.83164 | 810.54 | 11.81 | 1211 | 14.57 |

Table 5.1: Parameters for the center of the NOνA detector at the Ash River site. The angle in the table is the full space angle relative to the NuMI beam.

A cross section through the Far Detector Hall as seen by the NuMI neutrino beam is shown in Figure 5.5. The below grade portion of the building is 350 feet long, 63 feet wide, 67 feet high, and is constructed approximately 40 feet below the existing grade in granite rock. The below grade portion of the building will provide 100% secondary containment for the liquid scintillator used in the detector. The roof of the building consists of 1.5 feet of cast-in-place concrete over 2.5 feet of precast concrete planks. This composite section provides support for 0.5 feet of loose barite (barium sulfate) roof ballast to reduce the background rate from electromagnetic cosmic rays. The sides of the building above ground are shielded with granite spoils from the excavation. Details of this conventional construction are found in Chapter 9.

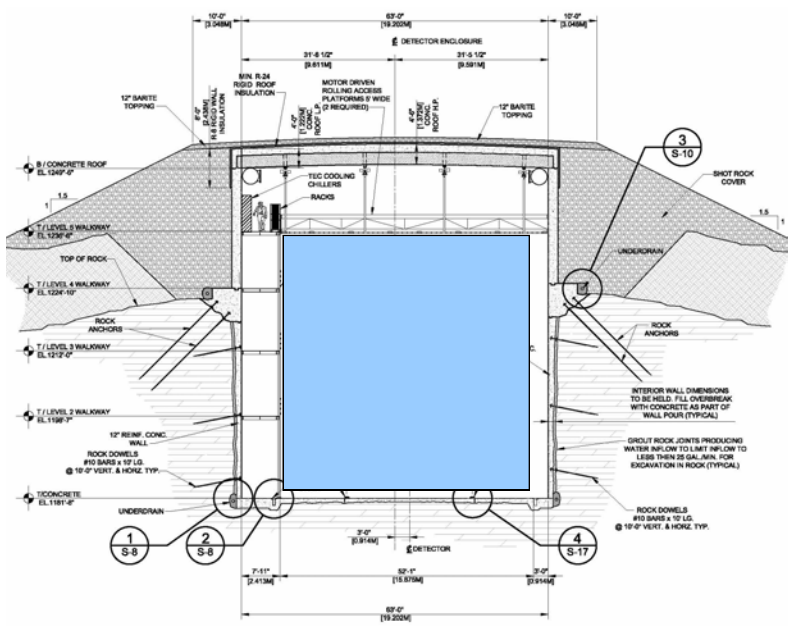
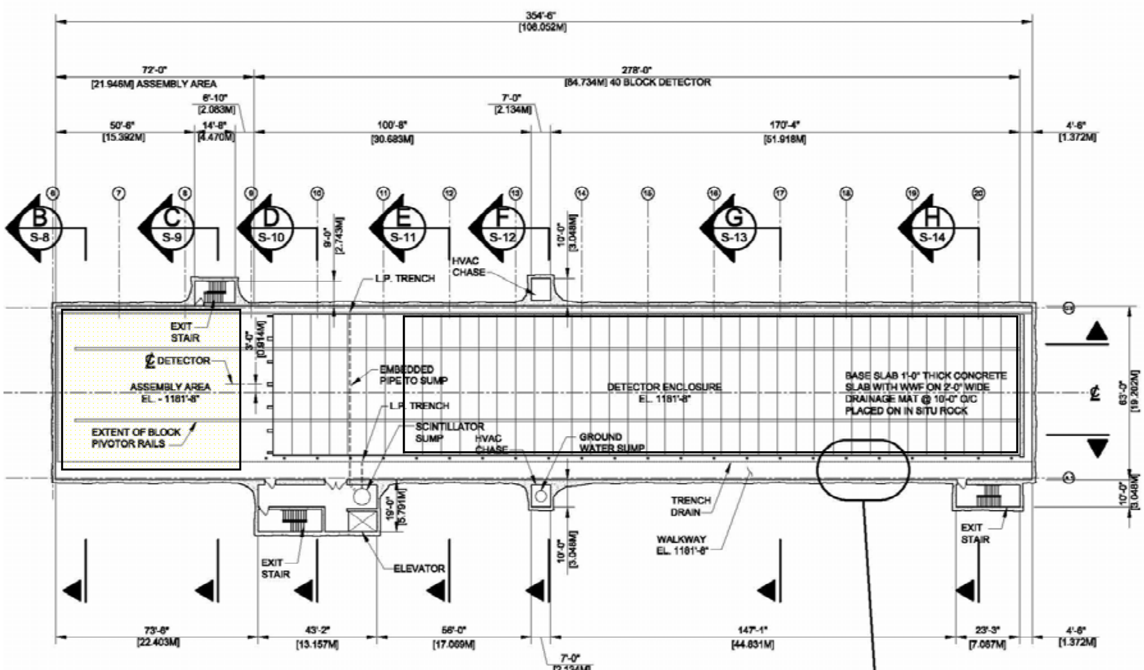



Fig 5.5: Neutrino beam view of the NOνA Far Detector Hall. The detector face is shaded blue. The detector is accessed via catwalks on one side and a rolling access platform suspended from the ceiling. The soil (light gray) has been removed at the detector site for excavation into the granite (block gray). The spoils from the excavation are loaded back on the sides of the detector to a minimum shield depth of 3m.

The plan view of the detector is shown in Figure 5.6. The detector sits in the south end of the building next to an assembly area also below grade. A loading dock and tanker truck delivery area (not shown) are at grade at the north end of the building. A longitudinal cross section through the building is shown in Figure 5.7 at the same scale as the plan view in Figure 5.6. This illustrates that the detector area is sized for an 18 kiloton detector, allowing later consideration of additional mass if the project can earn sufficient contingency.




side with an assembly area (yellow) to the right of the detector. A loading dock area (not shown) is located to the left of the assembly area with recessed and drive-in truck bays. A scintillator tanker handling area (not shown) is further to the left of the loading dock.

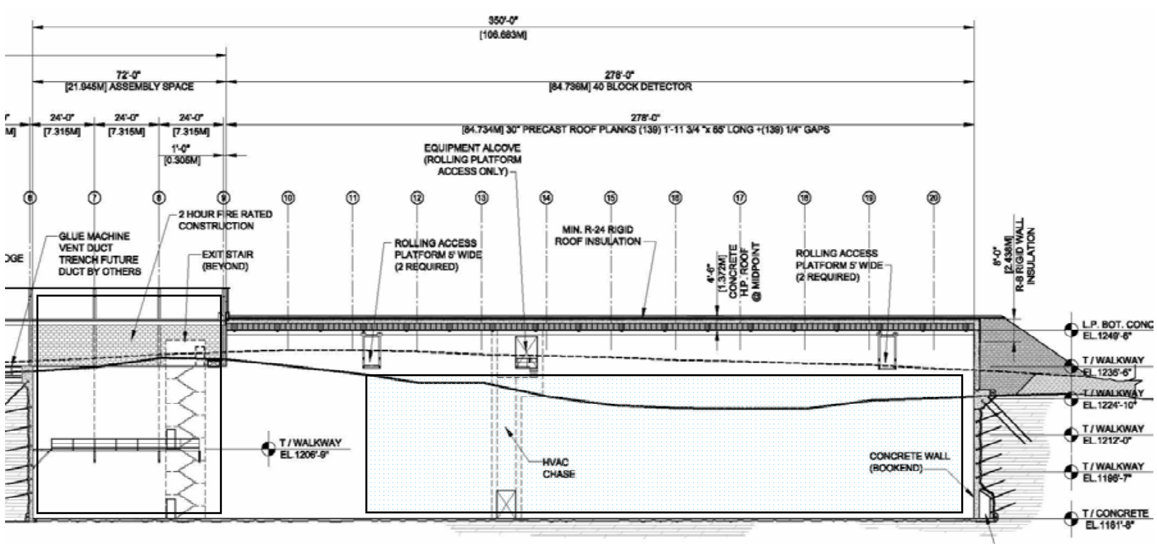



Fig 5.7: A longitudinal cross section through the building showing the detector and assembly areas below grade.

## 5.4 Near Detector Site and Detector Area at Fermilab

The NOνA Near Detector will be located in a new underground cavern off the existing MINOS access tunnel as shown in Figure 5.8. This new cavern requires a modest excavation of about 750 cubic yards of rock. Access to the area is via the existing MINOS shaft.

This Near Detector site will be located 1015 meters from the NuMI Target Hall and 105 meters below grade. The cavern is on a level grade and the NuMI neutrino beam enters the area from above at an angle of 58 milliradians (~3 degrees). At Ash River the beam enters the Far Detector from below at an angle of 58 milliradians. The cavern and Near Detector are located off-axis at the same angle of 14.6 milliradians as the Far Detector in Ash River as illustrated in Figure 5.9. Chapter 16 discusses the Near Detector cavern and Near Detector in detail.

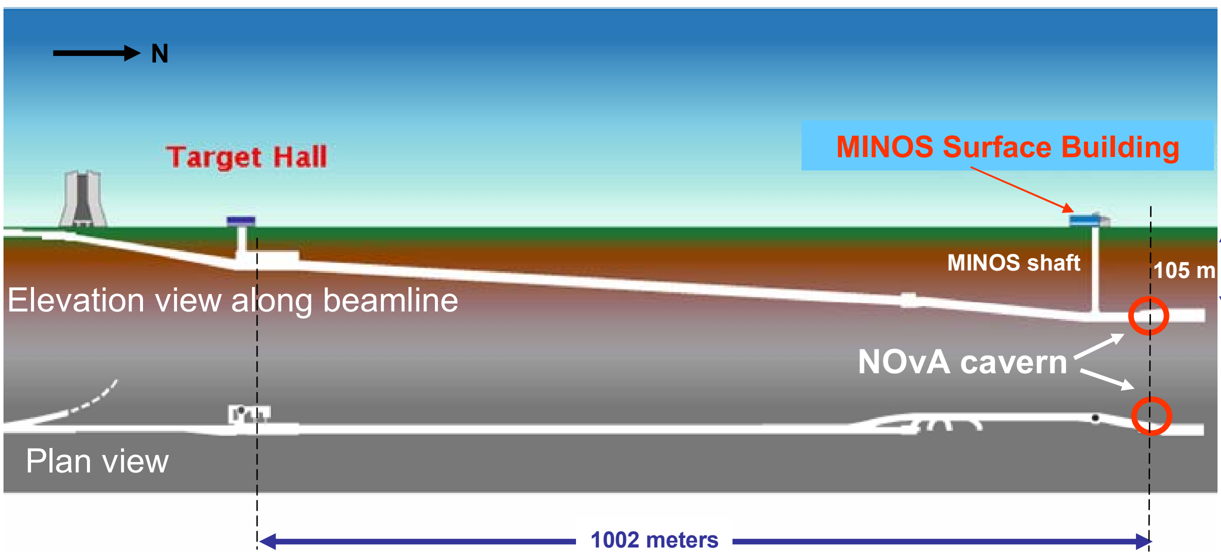



Fig. 5.8: Plan view and elevation (top) views of the NuMI beam line at Fermilab. The NOνA Near Detector will be located in the underground tunnel in the area labeled "NOνA cavern".

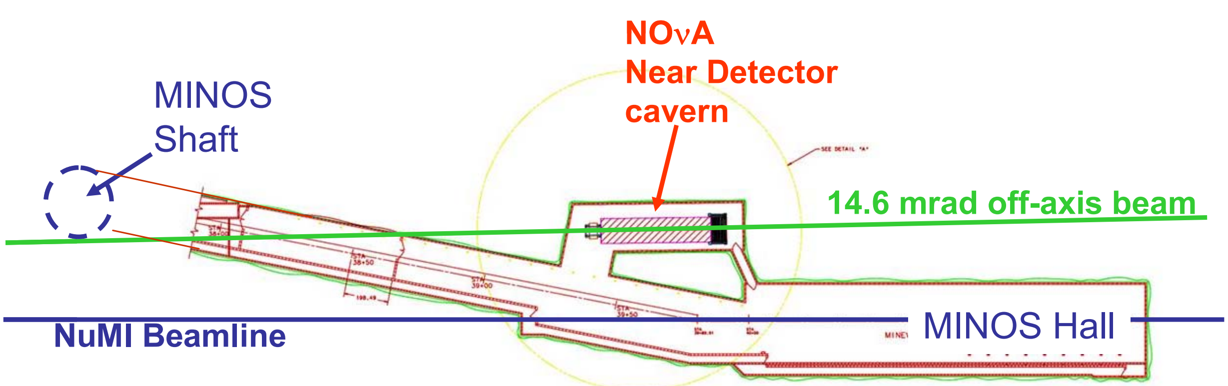



Fig. 5.9: A detailed plan view of the MINOS access tunnel from the vertical MINOS shaft to the MINOS hall. The new NOνA cavern is indicated.

## 5.5 Description of the NOνA Detectors

### *5.5.1 The Basic NOνA Detector Element*

The basic unit of all the NOνA Detectors is a simple rectangular rigid PVC plastic cell containing liquid scintillator and a wavelength-shifting fiber. This is illustrated in Figure 5.10. Charged particles traverse the cell primarily along its depth (D) and scintillator light is produced in the liquid. The light bounces around in the rectangular cell of width W, depth D, and length L until it is captured by a wavelength-shifting fiber or absorbed by PVC or scintillator. The fiber is twice the length L of the cell and is looped at the bottom so the captured light is routed in two directions to the end (top in the illustration) of the cell. Effectively there are two fibers in the cell, each with a nearly perfect mirror at the bottom so that nearly four times the light of a single non-reflecting fiber is captured. At the top of the cell both ends of the looped fiber are directed to one pixel on an Avalanche Photodiode (APD) photodetector array and the light is converted to an electronic signal.

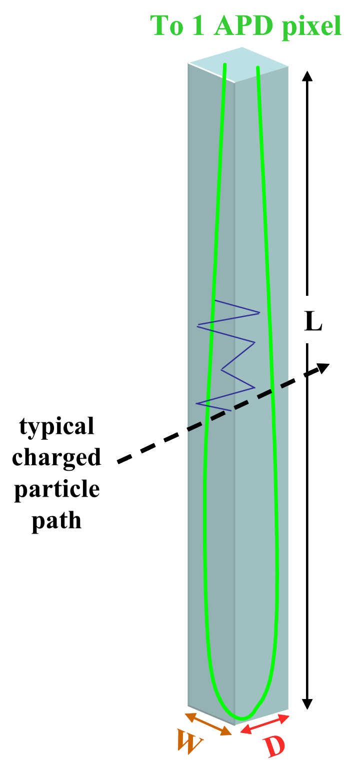



Figure 5.10: A PVC cell of dimensions (W, D, L) containing liquid scintillator and a wavelength-shifting fiber (green). A charged particle incident on the front face produces light (blue line) that bounces off the cell walls until absorbed by the fiber. The fiber routes the light to an APD.

The NOνA cell is made of a highly reflective titanium dioxide loaded rigid PVC cell with walls 2 to 4.5 mm thick. The cells have an interior width of 3.8 cm transverse to the beam direction, an interior depth of 5.9 cm along the beam direction, and an interior length of 15.5 meters. The cell width and depth satisfy the scientific requirements and the cell length is sized to fit on a standard domestic 53-foot semi trailer truck. To achieve the 15 kiloton mass stipulated by the scientific requirements, we repeat the cell structure 385,000 times.

### 5.5.2 *Liquid Scintillator*

Seventy percent (~ 10.5 kilotons) of the NOνA detector mass is the liquid scintillator held inside the NOνA cells. The 3.9 million gallons of liquid scintillator is composed primarily of mineral oil with 4.1% pseudocumene [1,2,4-Trimethybenzene] as the scintillant. The pseudocumene produces light with a spectrum peaked at 360 - 390 nanometers (nm). The liquid also contains chemical additives to shift the initial light to 400 - 450 nm matched to the wavelength-shifting fiber absorption spectrum. These additives are PPO [2,5-diphenyloxazole] and bis-MSB [1,4-di(methylstyryl)benzene]. An anti-static agent is added to the liquid at the level of 3 parts per million to prevent charge build-up during distribution to the cells. Blending of the scintillator components will take place at a toll blender in the Chicago area. Details of the NOνA liquid scintillator are discussed in Chapter 10.

Liquid scintillator mixtures like these are well known to have a ~ 20% decreased light output when exposed to oxygen, so the NOνA design requires only the lower oxygenated light level . Oxygen diffusion over time through the PVC walls is sufficient to produce the decreased light output effect. Since the scintillator light in a NOνA cell is captured locally by a wavelength-shifting fiber within about one meter path in the liquid, the attenuation length of the scintillator in NOνA is less of a performance driver than in previous experiments [7,8] where the light had to travel many meters through the liquid to the photodetector.

### 5.5.3 *Wavelength-shifting Fiber*

The NOνA detector contains about 13,000 kilometers of wavelength shifting fiber, with each 15.6 m long cell containing a loop of about 33.5 meters. The fiber captures the blue 400 – 450 nm light from the scintillator and wavelength shifts to green light in the range 490 - 550 nm. The fiber is 0.7 mm in diameter with a core of polystyrene mixed with 300 parts per million R27 dye as the wave-shifter.

The fiber is double clad with material of a lower refractive index than the core to facilitate total internal reflection of the shifted light along the fiber to the APD. The first cladding is a thin acrylic layer (PMMA or polymethylmethacrylate) and the second cladding is a fluor-acrylic, both claddings are about 3% of the fiber diameter. A similar fiber (but diameter of 1.2mm) was used in the MINOS detector [9].

As the internally reflected light travels down the 15.7 meter long fiber, it is attenuated by about a factor of ten with red light (520 – 550 nm) preferentially surviving. This property puts a premium on use of a photodetector with good quantum efficiency in the red and the APD is such a device. Chapter 11 contains more details on the fiber.

### 5.5.4 *Rigid PVC Extrusions*

The mass of the rigid PVC extrusions is ~ 4.5 kilotons or about 30 % of the mass of NOνA. Assembling 385,000 objects is achieved by using larger rigid PVC extrusions with 16 cells extruded together in a unit 0.635 meters wide as shown in Figure 5.11. Two different extrusions are required. The horizontal cells have exterior PVC walls 3 mm thick with 2 mm thick interior webs between cells. The vertical cells contain more PVC with 4.5 mm thick exterior walls and 3 mm thick interior webs. The extrusion thickness is 6.6 cm for both types, so the interior cells of the horizontals and verticals are slightly different in size. About 24,000 of the 16-cell extrusions are needed for the full detector.

The material properties of rigid PVC strongly influence the NOνA design. Unlike metals, plastics under stress can creep and perhaps creep to failure. The NOνA vertical cells build up an interior hydrostatic pressure of 19.2 psi at the bottom of the 15.7 meter column of scintillator (only 1.6 psi is seen at the “bottom” of a horizontal extrusion which is only 1.3 meters “tall”), so creep is a relevant concern. The NOνA extrusion design with the scalloped rounded corners between cells is designed to minimize the stress and therefore minimize the creep. Chapter 12 has a more detailed discussion of the creep properties of the custom NOνA PVC formula.

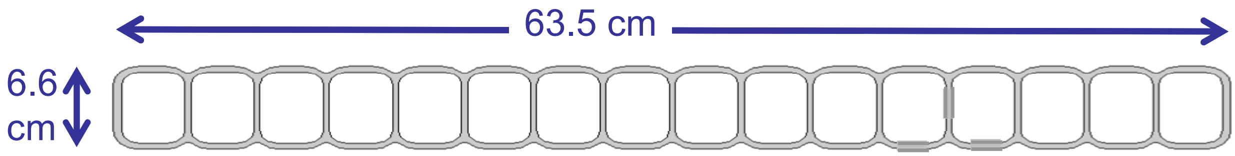



Fig. 5.11: Drawing of the NOνA rigid PVC extrusion.

The other crucial property of the PVC is its reflectivity for scintillator light of 400 – 450 nm. The light typically bounces off the PVC walls about 8 times before being captured by the fiber, so the surviving light at that point is proportional to the reflectivity raised to a power equal to the number of reflections, $(\text{reflectivity})^8$. A 1% change in reflectivity translates into ~ 8% change in the amount of light seen by the fiber. Our baseline rigid PVC sample has demonstrated a reflectivity of ~ 90% at 430 nm using a PVC mixture loaded with 15% of the anatase form of titanium dioxide which boosts the reflectivity in the blue region. Additional details of NOνA PVC properties and NOνA extrusions are covered in Chapter 12.

### *5.5.5 Extrusion Modules*

Two factories within the NOνA Collaboration construct leak-tight NOνA extrusion modules from the PVC and fiber. The first factory at Fermilab takes raw extrusion deliveries from the extruder and has the primary purpose of checking each extrusion for structural integrity. The extrusions are sorted to remove any variations in thickness which may arise during the extrusion process and additional sorting may take place to remove extrusions with excess "banana" along the length. The sorting will achieve a set of extrusions to form a single plane with a common thickness in the Far Detector at Ash River. Two sorted 16 cell objects are then attached with methyl methacrylate adhesive and the extrusion module is cut to an exact length.

The second factory is at the University of Minnesota is where the extrusions are threaded with wavelength shifting fiber loops as in Figure 5.10 and each fiber is tested for continuity after installation. The extrusion modules are capped at one end by a simple PVC end plate to contain the liquid scintillator and are capped at the other end by a more complicated fiber manifold which contains the liquid (in horizontal modules) and also routes the 64 fiber ends to 32 APD pixels. This is shown in Figure 5.12. As part of the assembly procedure, the 64 fiber ends are constrained into a block to match the APD pixel array, potted in epoxy, and faced off with a fly cutter.

The assembled extrusion modules with fiber manifolds and end caps are 15. 7 meters long, sized to fit inside a standard domestic 53-foot semi trailer truck. The end plates and fiber manifolds link the entire 32 cells into a common liquid volume. Thus the 1.3 meter by 15.7 meter extrusion module forms the primary containment vessel for the liquid scintillator. Each vertical extrusion module holds about 256 gallons of scintillator and each horizontal module holds about 278 gallons. As part of the construction process, each completed extrusion module is tested for leaks before being shipped to the Ash River site.

Chapter 13 contains more details on the extrusion module assembly.

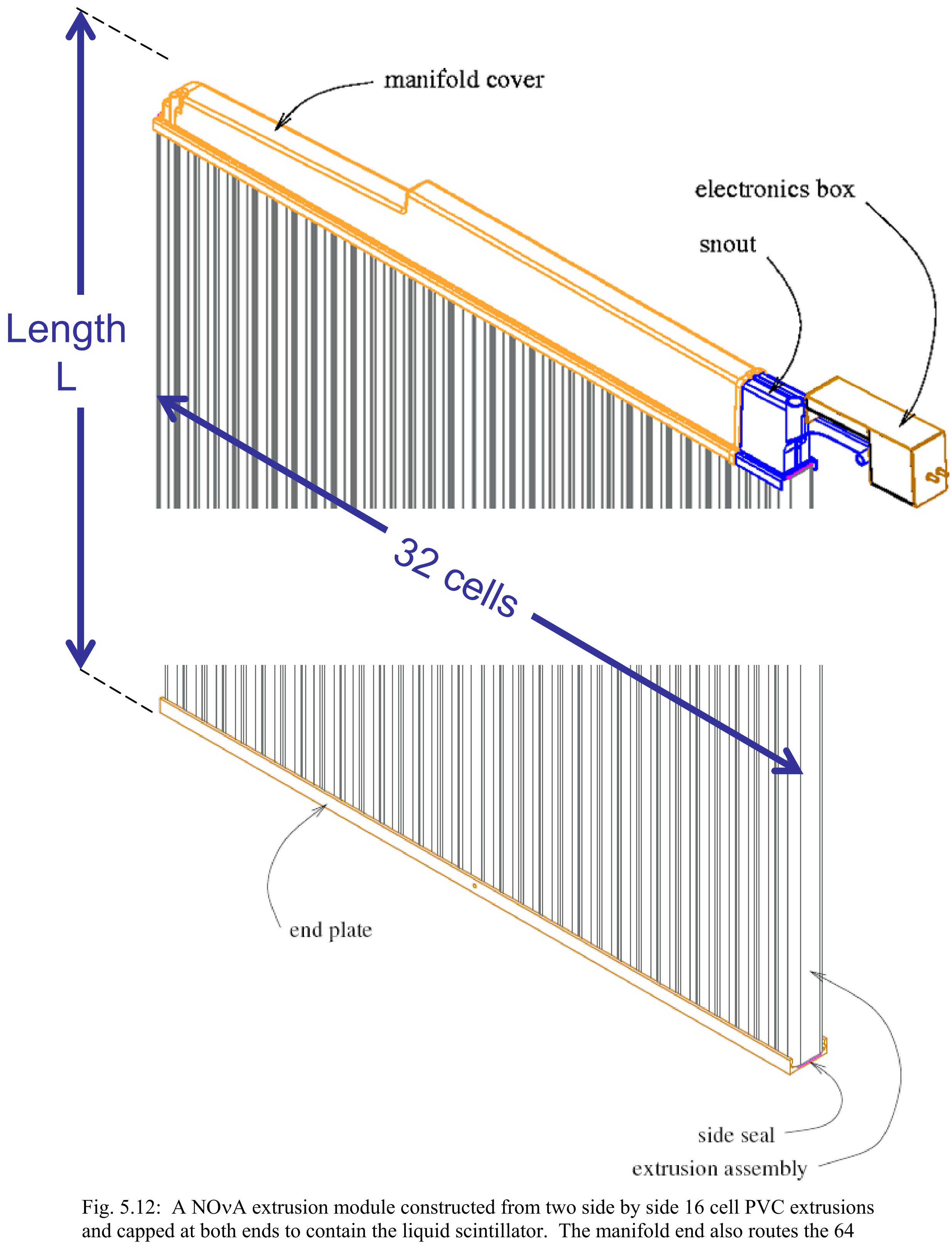



Fig. 5.12: A NOνA extrusion module constructed from two side by side 16 cell PVC extrusions and capped at both ends to contain the liquid scintillator. The manifold end also routes the 64 fiber ends to a cookie which couples to the avalanche photodiode array and associated electronics. The length L with the end plant and manifold is 15.7 meters for all the modules at the Far Detector site, but modules for the Near Detector are smaller.

### *5.5.6 Photodetector and Electronics*

The NOνA photodetector is an Avalanche Photodiode (APD) manufactured by Hamamatsu and similar to the ones developed for use in the Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider [10]. The APD has an 85 % quantum efficiency for the 520 – 550 nm light exiting the fiber. We operate the APDs at a gain of 100 using an applied voltage of about 375 volts. The thermal noise generated in the APD is reduced by cooling the devices to -15$^{o}$C using thermo-electric (TE) coolers. Heat from the hot side of the TE coolers is removed by a water cooling system in the Far Detector Hall. There are ~12,000 APDs on front-end boards in NOνA, one per extrusion module.

The signals from the APD are amplified by a special low noise pre-amp based on the Fermilab MASDA chip [11] and that pre-amp is combined in a new NOνA custom ASIC with 8:1 multiplexers, each running at 16 MHz. The signals are digitized by quad 40 MHz ADCs using the AD41240 from CMS. The multiplexing level on this ASIC can be switched to a 2:1 mode and this effectively speeds up the Near Detector electronics by a factor of four to cope with the higher intensity environment.

The front-end electronics will operate in continuous digitization mode and will not require any external trigger or NUMI timing gate. Data will be time stamped and compared to a NUMI timing signal in the DAQ system to determine if the event was in or out of spill. Data from the ADC is sent to an FPGA where multiple correlated sampling is used to remove low frequency noise. This processing also reduces the noise level and increases the time resolution.

Additional details on the APD and front-end electronics are in Chapter 14.

### *5.5.7 Data Acquisition System*

The Data Acquisition System (DAQ) for NOνA is based on a standard Gigabit Ethernet network and commercial processor. The 14,000 front-end boards are connected in groups of 64 to 194 custom Data Concentrator board which then interfaces to the Ethernet network. The Ethernet network passes the data to a processing farm consisting of about 136 commercial PCs.

The NOνA front end electronics operates in un-triggered mode with data continuously being digitized, time-stamped, pedestal subtracted, and zero-suppressed. There is no spill trigger required at the front-end. The data must be buffered awaiting arrival of a spill trigger message. A spill signal is required to arrive within the buffering time so that the spill time can be correlated with the time-stamped data to determine if the hits occurred in or out of spill. There is no additional selection of in-spill data. All hits that occur in a 30 μs window centered on the 11 μs NuMI spill are recorded for further processing.

Randomly selected data for calibration and monitoring will be collected off-spill at a rate that is approximately 100 times higher than the in-spill rate. The overall data rate is driven by cosmic ray muons with approximately 200 hits per muon.

Chapter 15 contains details of the DAQ.

## 5.6 Assembly of NOνA Detectors

There are three NOνA detectors in the NOνA project: the Far Detector at Ash River, the Near Detector at Fermilab, and an Integration Prototype Near Detector (IPND) at Fermilab. The relative sizes of these detectors are illustrated in Figure 5.13.

All three detectors have an identical structure and are assembled in alternating layers of vertical and horizontal extrusions as shown in the inset to Figure 5.13. This layering organizes the detector into planes with 90$^{o}$ stereo for tracking of particles produced in neutrino interactions originating in the PVC and scintillator mass. The assembled set of cells acts as a fully active or total absorption calorimeter since 70% of the mass is active liquid scintillator. Pulse height information is obtained from each cell and the total charged particle energy of a neutrino event is formed from the sum of the pulse heights. The cellular structure makes the detector a tracking device as shown for a sample Monte Carlo generated event in Figure 5.14. This combination of calorimetry and tracking makes the NOνA detector capable of distinguishing signal neutrino events and of rejecting backgrounds to that signal as stipulated in the scientific design criteria of Chapter 4. Table 5.2 lists relevant parameters of the three detectors.

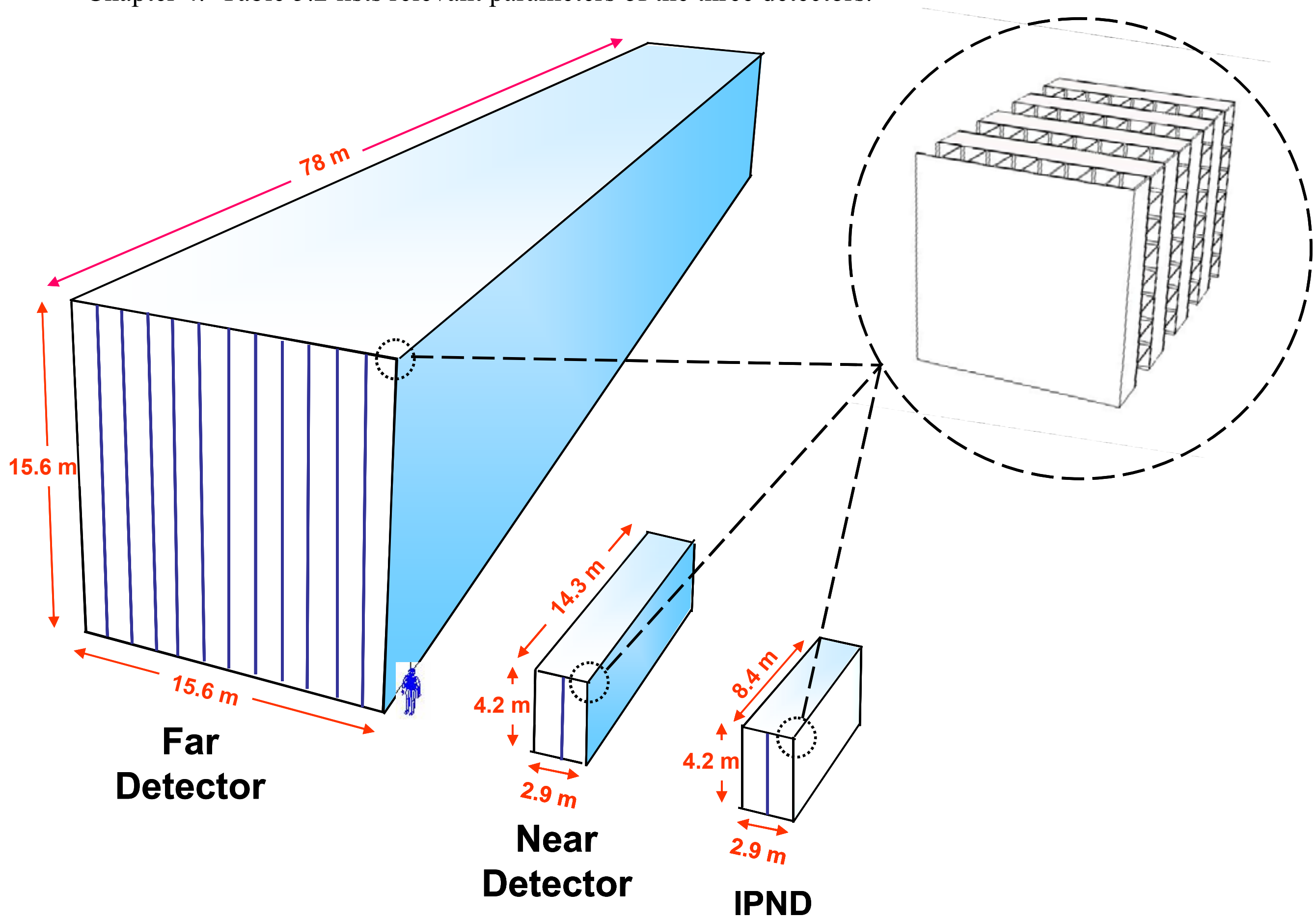



Fig. 5.13: The three NOνA detectors. The inset figure (dotted circle) shows that each detector has an identical alternating plane structure composed of vertical and horizontal cells like those shown in Figure 5.10.

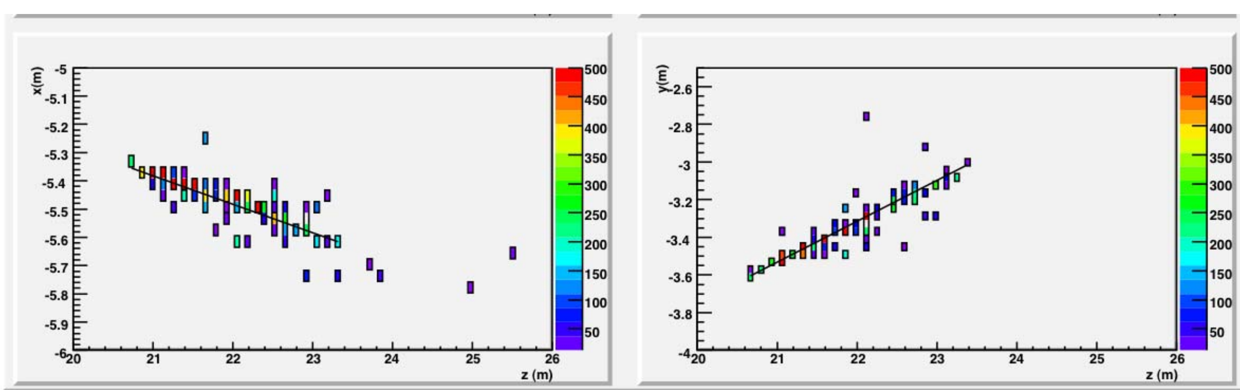



Fig 5.14: A simulated 2.2 GeV electron neutrino charged current event in the NOνA cell structure. The vertical cells are in the left diagram and the interleaved horizontal cells are in the right diagram. The color code indicates the relative pulse height in the cells.

| | Integration Prototype Near Detector (IPND) | Near Detector | Far Detector |
|---|---|---|---|
| Mass (metric tons) | 84 tons | 222 tons | 15,000 tons |
| Active Detector Size (width, height, length) in meters | ( 2.8 ,4.1, 8.4 ) | ( 2.8, 4.1, 14.3 ) | ( 15.6, 15.6, 66.9 ) |
| Liquid scintillator required (gallons) | 18,700 | 30,000 | 3,210,000 |
| Wavelength Shifting fiber required (kilometers) | 75 | 113 | 13,000 |
| Number of 32 cell extrusion modules required | 310 | 496 (310 get re-used from the IPND) | 12,036 |
| Number of extrusion modules seen by the neutrino beam (horizontal by vertical) | 3 by 2 | 3 by 2 | 12 by 12 |
| Number of detector channels | 9,892 | 15,904 | 385,152 |

Table 5.2: Parameters of the three NOνA detectors.

### *5.6.1 Integration Prototype Near Detector*

An early prototype of the Near Detector will be assembled as part of the R&D effort for NOνA. This prototype is called the Integration Prototype Near Detector (IPND) and it serves as a venue to test all the parts of the NOνA detector together beginning in calendar 2008. This integration is the main goal of the IPND.

The IPND consists of planes that are 64 cells wide (2 extrusion modules) and 96 cells high (3 extrusion modules), arranged in alternating horizontal and vertical layers and in segments of 31 planes. The 31 planes within a block are attached to one another with methyl methacrylate adhesive. The IPND length is four blocks of 31 planes.

The plan is to operate the IPND in the MINOS Surface Building shown in Figure 5.8 and Figure 5.15. The MINOS Surface Building is about 107 mrad off-axis to the NuMI beam and at this location a neutrino beam composed of 85 - 90% $\nu_\mu$ of energy ~ 2 GeV and 10 - 15% $\nu_e$ of energy ~ 1.3 GeV is available for studies with the prototype. The neutrino event rates per year for the MINOS surface building are shown in Figure 5.16 for Low Energy beam (see Chapter 2, Figure 2.1). The IPND has a fiducial mass of about 10 tons and the NuMI beam is expected to deliver about 3 x $10^{20}$ protons in a year during 2008 and 2009. About 2840 muon neutrino charged current events per year are expected in the energy range 1.6 – 2.4 GeV [12]. About 170 electron neutrino charged current events per year are expected in the energy range 0.5 – 2.0 GeV. In addition about 1100 neutral current events per year are expected in the energy range 1.6 – 2.4

GeV.  The IPND is of adequate length to contain 1.3 GeV electron neutrino events, but the 2 GeV muons will exit the back of the detector, allowing only a tag that they were muon events and not electron events.  While these samples are small, they should prove instructive to the NOvA simulation efforts.

Since the prototype detector is on the surface, the location also allows us to measure the unshielded cosmic ray backgrounds in the detector.

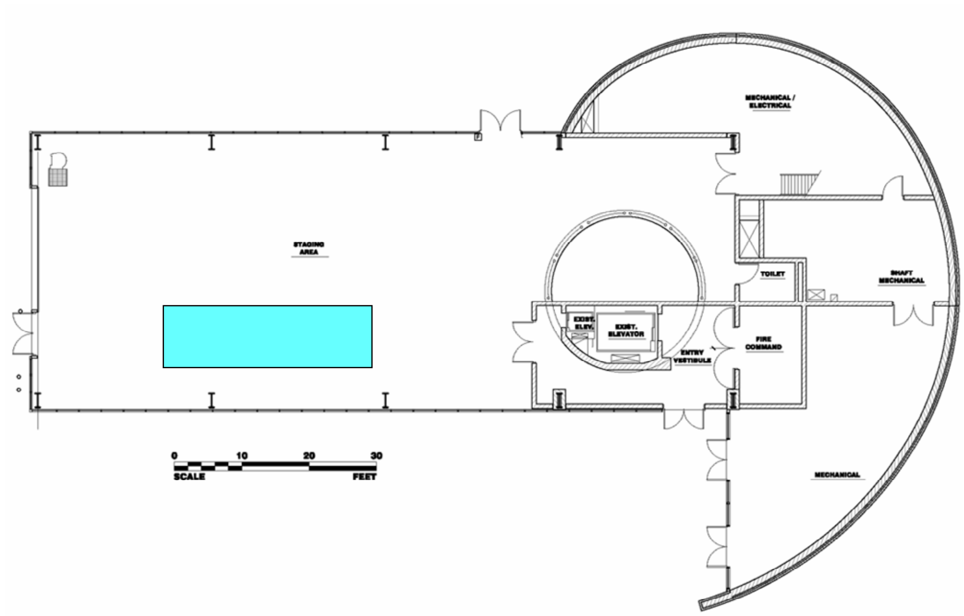



Fig. 5.15: Plan view of the NOvA IPND in the MINOS Surface Building.

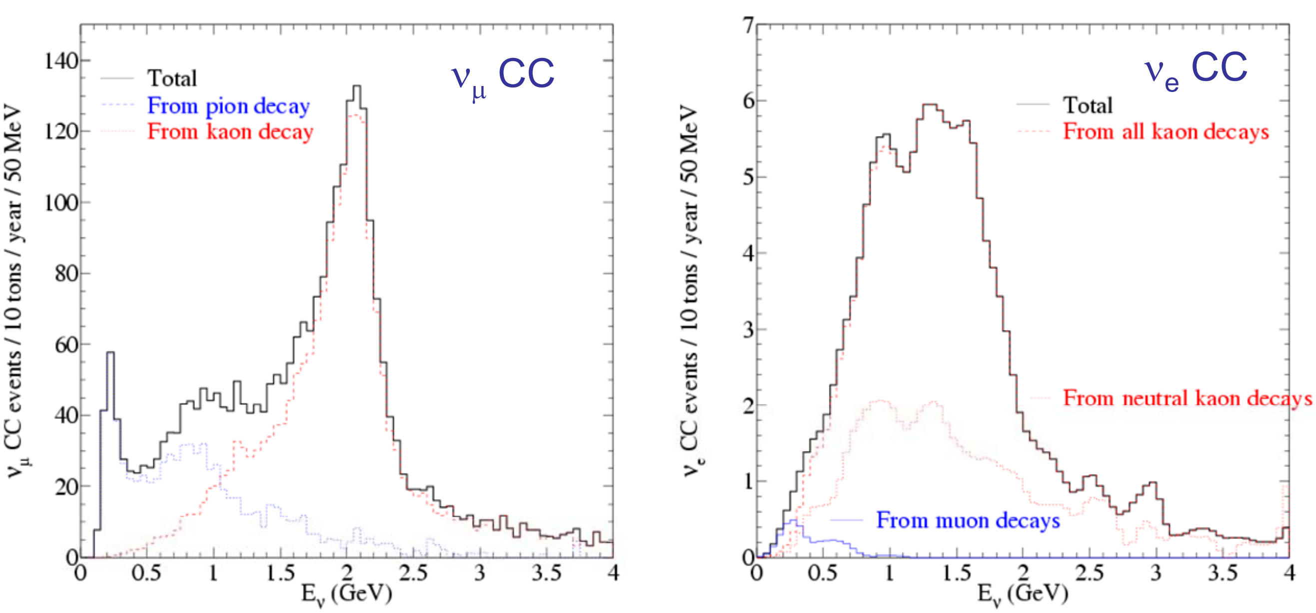



Fig. 5.16:  $\nu_\mu$ charged current (left) and $\nu_e$ charged current (right) event rates per year in the IPND at the MINOS surface building with the NuMI beam in Low Energy mode.

### *5.6.2 Near Detector*

The Near Detector is an identical copy of the Far Detector except that the extrusion modules are shorter to accommodate the restrictions of the NuMI underground tunnel and MINOS access shaft described in Section 5.3. A diagram of the Near Detector is shown in Figure 5.17. The detector consists of planes that are 64 cells wide (2 extrusion modules) and 96 cells high (3 extrusion modules), arranged in alternating horizontal and vertical layers and in segments of 31 planes. There are 6 blocks of 31 planes and an additional set of ten planes interspersed with planes of steel to tag muons from $\nu_\mu$ charged current events. Additional details are in Chapter 16.

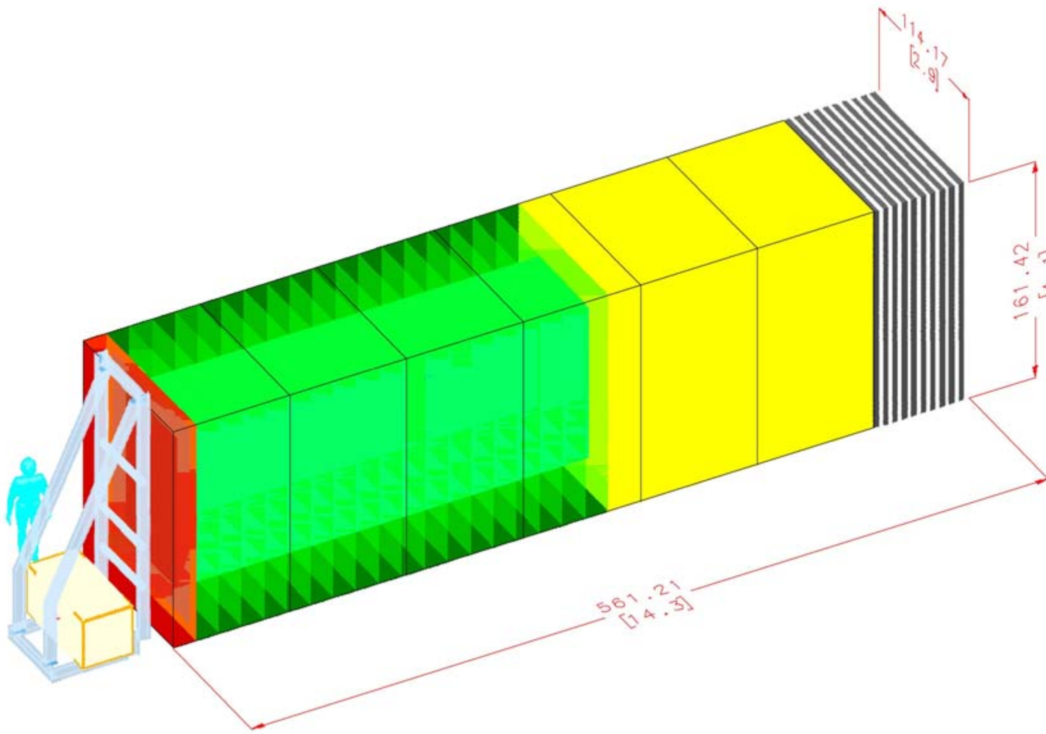



Fig. 5.17: The NOνA Near Detector constructed from 6 blocks of 31 planes plus a muon catcher. The beam comes from the lower left in this diagram. The upstream 6 planes form a veto region (red). The next 108 planes are the fiducial region (green) with transverse containment indicated. The fiducial volume is followed by a 72 plane shower containment region (yellow). All parts of these three sections are fully active liquid scintillator cells identical to the Far Detector and the colored areas just represent a logical assignment. Downstream of this active region is a 1.7 meter long muon catcher region of steel interspersed with 10 active planes of liquid scintillator (black and white).

### *5.6.3 Far Detector.*

Twelve of the extrusion modules get placed side by side on a flat assembly table to form one plane of the NOνA detector. Thirty-one such planes are bonded together with methyl methacrylate adhesive (MMA) into a block to form the strong honeycomb-like structure shown in Figure 5.13. 120 metric tons of MMA are required for the full 15 kt detector, and this places requirements on the building ventilation system due to an OSHA 100 ppm limit (ACGIH TLV 50 ppm limit) [13] for MMA vapors in workspaces. MMA has been selected as the adhesive because it has the largest shear and peel strength of all the adhesives tested to date, and high strength is required for this five story tall PVC object.

A custom vacuum lifting fixture will be used to move the modules from incoming truck pallets to a custom glue machine for the MMA application and then onto the flat assembly table. The 31 plane blocks are constructed so that vertical planes of extrusion modules all have their readout fiber manifolds at the top of the detector. Horizontal planes of extrusions have all readouts on the west side (left of the beam) of the detector.

Each 31 plane block is 15.65 meters wide by 15.65 meters high by 2.05 meters thick. The PVC in a 31 plane block has a mass of about 139 metric tons. When filled with scintillator, the mass of a 31-plane block is about 460 metric tons. The empty 31-plane block is assembled in a horizontal position, moved down the Far Detector Hall to the previously constructed blocks, and then rotated 90 degrees into a standing position using the custom block pivoter machine illustrated in Figure 5.19.

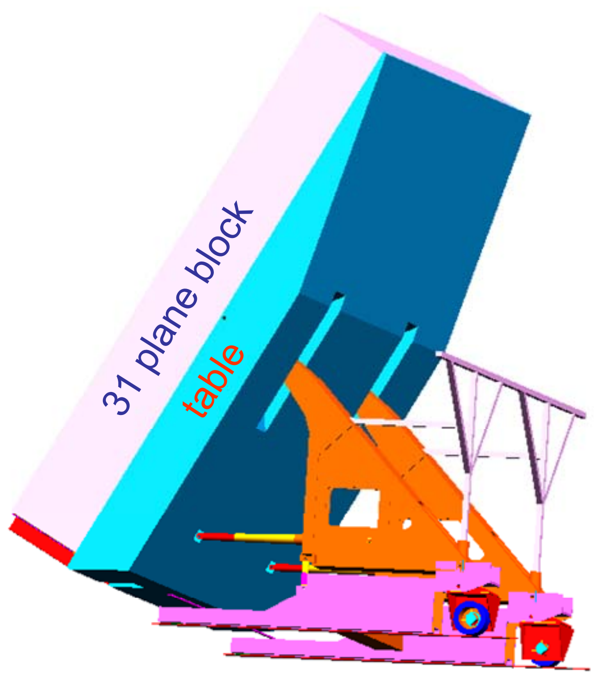



Fig. 5.19: The custom NOνA block pivoter. The table starts as a horizontal assembly table and is then used to tilt a 31-plane block into the vertical position.

Five of the 31-plane blocks get attached to one another to form a detector "Superblock". The 31 plane blocks are nominally touching, but we assume we might leave a gap as large as 2 – 3 mm (~100 mils) on parts of the adjacent surfaces. Between Superblocks we deliberately leave a larger gap of 2 cemtimeters, chosen to be a large enough gap that we can verify it from the outside of the structure. This 2 cm gap is made explicit at the top of the blocks via a 2 cm spacer. This gap serves as an expansion joint (like those in a concrete sidewalk) so that when the Superblock is filled with scintillator the stress in the PVC will be limited. The Superblock swells when filled as shown in Figure 5.20 with its largest thickness about 1 meter off the floor. If all the Superblocks touched, then filling the blocks would drive the PVC stresses to unacceptably high levels. The expansion gaps are designed to limit the stress build-up and therefore limit the PVC creep discussed in section 5.5.4.

A total of 6 Superblocks plus one smaller set of 3 blocks comprise the full 1003 planes in the NOνA Far Detector. The detector is built from south to north, starting against a strong bookend at the south end of the building. When all 33 blocks are in place, the block pivoter is braced to form a north bookend as shown in Figure 5.21.

The large NOνA PVC structure is unique and we have spent considerable time understanding the properties of rigid PVC and the properties of our structure. Calculations have been done via finite element analyses and confirmed with calculations and tests of small models. These details are presented in Chapter 17.

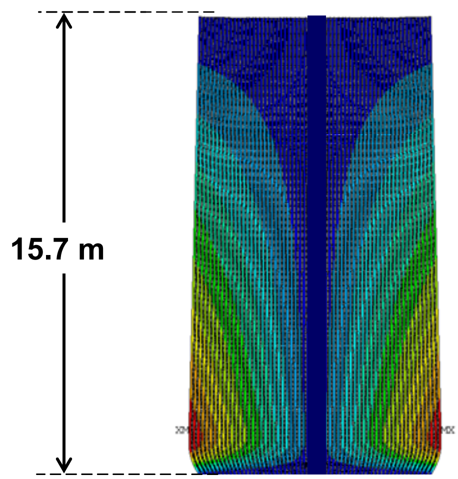



Fig 5.20: A NOνA Superblock of 155 planes showing the swelling that occurs near the bottom of the block when all the extrusions are filled with scintillator. The horizontal scale is exaggerated with the maximum (red) areas representing a horizontal increase of order 20 mm out of 10 meters.

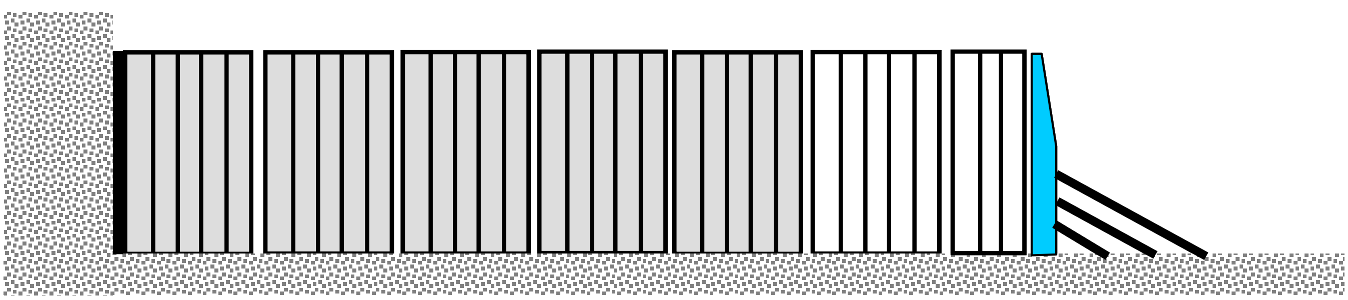


Fig 5.21: The full NOνA Far Detector composed of 6 Superblocks and a 3 block section. Expansion gaps are shown between the Superblocks. The detector is built from left to right starting against a strong bookend and assembly ends with the conversion of the block pivoter into another bookend at the right end. This figure shows 5 of the superblocks full of scintillator with 2 blocks yet to be filled.

Filling the blocks with liquid scintillator is a separate assembly operation and takes place after the blocks are attached to the full detector. To avoid a long serial schedule for completion of the detector, we fill the structure with scintillator almost in parallel with the PVC plane erection, following the empty PVC module assembly front by one Superblock (5 blocks) in a total 24 month schedule. The required scintillator fill rate of about 18 gallons per minute is accomplished with a custom metering machine which fills eight extrusion modules in parallel.

Outfitting of the detector with electronics follows the filling task with about a one month delay per block. Therefore the Far Detector becomes active linearly throughout the ~ 24 month assembly period.

## 5.7 Summary of Design Changes since the Conceptual Design Reports

The NOνA detector project and the Accelerator & NuMI upgrade project required for NOνA were merged into a single project with common contingency. Prior to January 2007 these were separate projects. In January the project also received target guidance from DOE for a TPC of $ 260 M. Most of the changes to NOνA since the two CDRs stem from value engineering studies done to keep the cost of the project within this cost envelope while preserving the scientific goals. This section outlines these changes so that the reader can compare the TDR to the CDRs.

### *5.7.1 Major Changes*

The NOνA detector mass was reduced from 25kt to 15 kt. The loss of detected neutrino events was partially compensated by changing the planned five year data run of the detector to six years. Continuing work on the algorithms for neutrino event reconstruction also resulted in an increased detection efficiency of 26% compared to 24% in the CDR. This also partially compensated the reduced mass.

The small service buildings for the Accelerator & NuMI upgrade part of the project were removed from the project scope. These buildings are needed for the Fermilab program even if NOνA is not constructed. Similarly the number of kicker systems for NOνA was reduced from five to four by removing one kicker from the project scope. This kicker is required for gap clearing in the Main Injector during Collider and MINOS running and is needed even if NOνA is not constructed.

### *5.7.2 Accelerator and NuMI Upgrades*

- The injection line design was changed to simplify installation and to minimize the number of powered elements near the Recycler Ring. The main design change in the extraction line was to move the injection point in the Main Injector. This allows use the same ceramic beam tube and magnet for this kicker as those planned for the Recycler extraction and abort kickers, thus eliminating a separate design for both the ceramic beam tube and the magnet.
- The design was changed to accept 81 Booster bunches per Booster batch instead of 82. This change loosens the kicker rise/fall time specifications from 38 nsec to 57 nsec with ~1% loss of protons to the NuMI target. Corresponding losses elsewhere in the accelerator complex have been studied and can be controlled.
- The kicker designs were further optimized and flattop bumper systems were removed.
- A simpler replacement device for the hole left after moving Horn 2 was devised.

### *5.7.3 Site and Buildings*

- A larger site at Ash River has been stipulated for spoils piles during construction.
- The Far Detector Hall has been reduced to hold a maximum 18 kt detector instead of 30 kt.
- The loading dock in the Far Detector Hall was reduced by one 24 foot long bay.
- The orientation of the Far Detector hall was flipped (north / south ends interchanged) to keep liquid scintillator deliveries further away from the Ash River. This allows detector construction to proceed from south (Fermilab end) to north and simplifies commissioning of the detector.

- The Far Detector Hall roof design was changed from steel trusses supporting a granite spoils overburden to pre-tensioned concrete planks.
- The shielding overburden on the Far Detector Hall was enhanced with 6 inches of barite to reduce the number of electromagnetic cosmics entering the detector unseen.
- The side berm shielding on the north end of the building was removed when Monte Carlo studied indicated that the shield was only needed for events appearing to come from within 45 degrees of Fermilab. The NOνA reconstruction software can distinguish the incoming direction of events outside this 45 degree cone..
- A ventilation system for MMA vapors was added to the Far Detector Hall.
- The detector position within the Far Detector Hall was moved to one edge (east) of the building to reduce number of catwalks.
- The number of catwalks was further reduced by having each catwalk access three horizontal layers instead of just two layers.
- The Far Detector Hall loading dock level was changed to match the top catwalk level, providing ease in construction as most cable tray, cable, racks, power supplies and other infrastructure items are brought to the top of the detector from the loading dock.

### *5.7.4 Scintillator*

- The scintillator quantity was reduced to the amount needed for 15 kt.
- The fluor (pseudocumene and waveshifters) content in the scintillator was reduced while preserving enough light to meet the scientific performance requirements.
- Scintillator blending will now take place at toll blender in the Chicago area instead of at a blending facility constructed on the Fermilab site. This allows larger batch sizes and a reduction in cost.

### *5.7.5 Fiber*

- The fiber quantity was reduced to the amount needed for 15 kt.
- The fiber diameter was reduced from 0.8 mm to 0.7 mm to reduce cost and to reduce risk from the bending radius of the fiber at the end of each cell.

### *5.7.6 PVC Extrusions*

- The PVC quantity was reduced to the amount needed for 15 kt.
- The reflective component of the PVC resin was changed from Rutile $TiO_2$ to Anatase $TiO_2$ to increase the reflectivity of the PVC extrusion cell walls. This increased the light collected by each cell by 15%.
- The 32 cell extrusions are now made by gluing two 16 cell objects side by side instead of having a single 32 cell object from a single expensive extrusion die.
- The extruder vendor now also serves as a buffer for output of extrusions before shipping to the Extrusion Module factory. This removes risk in the tightly coupled pipeline of PVC extrusions from extruder to factory to Ash River.

### *5.7.7 Extrusion Modules*

- The number of module factories has been reduced from three to one. This allows a single set of factory tools to perform the entire job and avoids complicated shipping schemes from three factories to the Ash River site. Instead the one factory now has a warehouse space to buffer the output of the factory.

### *5.7.8 Electronics and DAQ*

- The APD quantity was reduced to the amount needed for 15 kt.
- The multiplexing level for the Near Detector electronics was changed from 8:1 to 2:1 to effectively speed up the readout by a factor of four. This allows better Near Detector performance in the higher event occupancy environment at Near Detector site.

### *5.7.9 Near Detector Site and Assembly*

- The Integration Prototype Near Detector (IPND) is now shortened to four blocks instead of six.
- However, all four blocks of the IPND are now re-used in the final Near Detector instead of three out of six.
- The Near Detector has been rotated to the proper off-axis angle in a new cavern off the MINOS access tunnel. This now satisfies a new scientific performance requirement which was developed after Monte Carlo studies of the Near Detector orientation. This also removes risk of compromising the secondary containment if the NOνA detector were sitting in a passageway used by others as in the CDR.

### *5.7.10 Far Detector*

- The assembly adhesive has been changed to a Methyl Methacrylate adhesive for the PVC planes to increase the safety factor of the construct. This added cost since it put a more severe requirement on the Far Detector Hall ventilation system.
- The Block raiser is now a block Pivoter. Completed 31-plane blocks are rotated about a point near the center of mass of the table + empty block instead of being lifted from the floor.
- All the horizontal modules are now read out on the west side of the detector instead of interleaving alternating east and west readout in successive planes. This reduced the performance of the detector slightly, but allowed cost savings from the reduced number of catwalks required for detector access.
- The cosmic shield wall on the north end of the detector has been removed following Monte Carlo studies which show that cosmic ray induced events from the north cannot be mistaken for events originating from a neutrino beam from Fermilab (from the south).

## 5.8 Value Engineering Continues

The list of changes in Section 5.7 is the result of a continuous value engineering process done since the Conceptual Design Report. This value engineering will continue as we complete the final designs and test those designs with prototype structures and in the Integration Prototype Near Detector.

## 5.9 Chapter 5 References

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[2] NOνA Project Management Plan, NOVA-doc-129. See Appendix A of this TDR.
[3] draft Storm Water Pollution Prevention Plan (SWPPP), NOVA-doc-1324.
[4] draft NOνA Environmental Assessment, NOVA-doc-2672 and NOVA-doc-1354.
[5] NOνA Environmental Assessment Worksheet, NOVA-doc-205.

[6] Steve Dixon, American Engineering Testing, Inc Report of Subsurface Boring and Piezometer Installation, NOvA Off-Axis Site, NOvA docdb note 162, November, 2005. See also NOvA docdb note 108, Preliminary Ash River Boring Logs, October, 2005.
[7] Some examples are: M. Ambrosio et al., the MACRO detector at Gran Sasso, NIM A 486 (2002) 663-707, D. Harris et al., Precision calibration of the NuTeV calorimeter, NIM A447 (2000) 373-415, L. Ahrens et al., A Massive, Fine-grained Detector for the Elastic Reaction Induced by Neutrinos in the GeV Energy Region (BNL-734), NIM A254 (1987) 515-528.
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[10]K. Deiters et al., NIM A461 (2001) 574-576, NIM A453 (2000) 223-226, and NIM A442 (2000) 193-197.
[11] M. Maolinbay et al., NIM A485 (2002) 661-675, and T. Zimmerman, Fermilab Technical Note FERMILAB-TM-2063 (1998).
[12] M. Messier, NuMI Surface Building and Near Detector Fluxes, NOVA-doc-931.
[13] OSHA (Occupational Safety and Health Administration) and ACGIH (American Council of Governmental Industrial Hygienists) limits quoted in the Devcon Plastic Welder MSDS (Material Data Safety Sheet).