Assessing and Installing Avalanche Photodiodes on the NOvA Near Detector

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Abstract

As of today, scientists suspect that neutrinos played a vital role in the evolution of the universe, contributing to all existing matter in the cosmos. How that evolution occurred still remains a mystery due to our lack of understanding of the puzzling properties of neutrinos. The NuMI Off-Axis υ_e Appearance (NOvA) experiment will seek to find some answers by studying neutrinos in order to understand matters as flavor state oscillation, mass hierarchy, and symmetry between matter and antimatter. Two massive detectors are being used: a 300 ton near detector at Fermi National Accelerator Laboratory (Fermilab) and a 14 kiloton far detector in Minnesota located 810 km away. To actually discern the presence of neutrinos, thousands of photodetectors are utilized to detect light as neutrinos interact with atoms of liquid scintillator. The scintillator light that is emitted will be transferred by wavelength-shifting (WLS) fibers to the photodetectors. Afterwards, the light is then converted into electrical pulses and recorded digitally.

1. Introduction

In 1930, Wolfgang Pauli postulated the existence of a weakly interacting electrically neutral particle with the same spin as an electron, but with virtually no mass. His theory came about in a critical period. At that time, a problem had confounded physicists concerning nuclear beta decay. As a radioactive nucleus ejected an electron, scientists observed that the electron did not have a distinct value of energy. In fact, it had a continuous spectrum of energies that contradicted the laws of energy and momentum conservation. In many instances, the total energy after the decay was less than before emission took place. This phenomenon of missing energy proved to be so disturbing that some scientists, such as Niels Bohr, were ready to abandon the law of conservation of energy completely [1].

It was at this pivotal time that Pauli provided what he called a “desperate remedy” to save the conservation laws. Pauli hypothesized the existence of electrically neutral particles that must be emitted along with electrons, carrying off the missing energy, but are difficult to detect. Four years later, Enrico Fermi formulated a mathematical theory supporting Pauli’s hypothesis and in 1954 Fred Reines and Clyde L. Cowan, Jr. provided the first experimental evidence that confirmed the existence of neutrinos by searching successfully for a distinct experimental signature in inverse beta decay [2]. In addition to the electron neutrino produced in nuclear beta decay, the existence of two other “flavors” of neutrino were discovered in 1963 (muon neutrino) and in 2000 (tau neutrino) [3].

Although the scientific community has been aware of the existence of neutrinos for over half a century, little is known about these elusive particles. For instance, after assuming for decades that neutrinos lacked mass according to the Standard Model of Particle Physics (Figure 1), the Super-Kamiokande Collaboration in 1998 and the Sudbury Neutrino Observatory in 2001 revealed evidence proving the theory that neutrinos do indeed have mass and actually transmute (or oscillate) from one neutrino flavor to another. The finding produced new questions pertaining to this phenomenon and ushered in a new age of particle physics, compelling such physicists as Prof. David Wark of Imperial College London to exclaim, “The discovery of neutrinos having mass could have amazing consequences for the universe” [4].

In order to take closer steps to better understand neutrinos, the NOvA project at Fermilab is being commissioned to study electron and muon neutrinos through the use of two giant neutrino detectors. A 300-ton underground near detector at Fermilab will sample muon neutrinos from the Neutrinos at the Main Injector (NuMI) beam (Figure 2) and a 14 kton far detector at Ash River, Minnesota will be 810 km away to detect neutrino oscillation (Figure 3). By studying the properties of neutrinos, NOvA seeks to address essentially two major questions. First, what are the masses of the neutrino types and what is the mass hierarchy of these particles? This information will help determine if neutrinos are their own antiparticles or not. Secondly, what is the symmetry between matter and antimatter? When the Big Bang occurred in the cosmos, there should have been equal amounts of matter and antimatter created. However, for the most part, antimatter appears to have vanished and matter to have flourished, producing stars, planets, cosmic dust, and even us. This phenomenon is known as Charge conjugation-Parity (CP) violation and we do not know why or how this asymmetry occurred. These questions and more seek to be addressed by NOvA [5]. My contribution to this enterprise was to assist with the quality assessment and installation of APDs, which are designed to detect neutrino events in liquid scintillator.

2. Progress

APDs are semiconducting devices that can convert light to electricity via the photoelectric effect. When a neutrino interacts with a nucleus of anthracene atoms (liquid scintillator), various charged particles such as muons or pions can be released. These charged particles can then excite the electrons of neighboring atoms and ultimately produce blue light in the range of 450 to 500 nm. That light is then captured and shifted to green light (~525 nm) by wavelength-shifting (WLS) fibers, and then is directed to a pixel of the APD (Figure 4). When an emitted photon travels from the fiber through the silicon substrate of the diode, it can transfer its energy to a bound valence electron, which can subsequently transport the electron into the conduction band. Through impact ionization, electron-hole pairs are thermally generated to produce an avalanche current as reverse bias voltage is applied (400 ± 50V). Through this mechanism, the photoelectron knocked off by the photon can initiate a continuous ionization cascade that can spread throughout the silicon, which will soon break down and become conductive [6]. Consequently, the original photoelectron is amplified into a readable current flow that can be recorded digitally.

In order to ensure optimal functionality of the photodetectors, each APD module (Figure 7) has to first survive a quality assessment (QA) test composed of five elements:

1. **Visual Inspection:** In this phase, I had to verify the cleanliness of the APD chip, the wiring of the capacitor, the integrity of the water hose, and the sturdiness of the elbows that allow dry air to flow through the APD assembly. Once completed, I then ran a device check (aka "Devcheck") by scanning the APD barcode and ensuring that cataloged information concerning the photodetector is in a database (Figure 8).

2. **Vacuum Test:** Dry gas is pumped into the APD module so as to maintain low humidity and prevent buildup of moisture on the pixels. In order to check if the system works, I had to ascertain whether air leakages occurred after the APD module was mounted onto an optical connector. For this test, an aluminum base with an o-ring groove, and connected to an air compressor, is utilized. An o-ring rubber band is placed in the groove to seal air and the module is carefully placed on top. Then about 24 in. Hg of air is pumped between the base and the assembly and left untouched for 10 to 20 minutes to see if the pressure gauge drops more than 0.5 in. Hg in 10 minutes or 1.5 in. Hg in 20 minutes (Figures 9

and 10). *This is the longest phase of the procedure and most failures occur here.*

3. **Flow-Through Test:** This test is performed to check if ventilation of the assembly properly permits the passage of air or if blockage is present.

4. **"Black Box" Test**: This trial identifies APDs that are malfunctioning by drawing microamperes of dark current on any given part of the 32 pixels of the APD array; a dark current is a relatively small electric current that flows through a light-sensitive device when no photons are entering. During this step, the assembly is placed over posts of a circuit board and its ribbon cable is fitted into a connector through which 375 V are supplied within 20 seconds (Figure 11). A computer program then records the IV curve to verify if the current is above the cut-off point.

5. **TEC Test:** This final measure is conducted on the thermo electric cooler (TEC) to confirm APD cooling so as to limit noise on the electronic readouts (Figure 12). Since the APD current is dependent on the thermal generation of electron-hole pairs, higher temperatures create additional charge carriers (electrons and holes) that increase the current with or without photons. Consequently, noise in the electronics can be amplified to the detriment of the experiment.

Assuming all five phases of the QA test are successfully completed, the APDs are shipped underground to the NOvA near detector and installed onto modules composed of PVC cells containing liquid scintillator and WLS fibers.

3. Installation of the APD Assemblies

In order to actually install the APDs onto the near detector, I first had to gain specialized training. The first training course was entitled "NuMI/MINOS Underground Safety Training," which sought to educate participants about the hazards, control measures, self-rescuer protocol, and access control procedures associated with working in the underground NuMI facility that contains the near detector. Additionally, I had to pass the "Fall Protection Orientation" in order to work on top of the near detector. For this class, fall prevention methods, fall hazard work rules, and a review of all fall protection equipment were introduced. In the end, I had to pass a 25-question test in order to complete the training course. Once all training was accomplished, I had full access to the detector and could contribute to the installation effort.

Installation of the APDs proves to be a straightforward process, but must be performed delicately to avoid damage to the photodetector. First an APD box is unsealed, exposing an optical connector connected to a front-end board (FEB); the optical connector directs 32 WLS fibers to each of the 32 pixels of the APD array and the FEB provides a built-in 32-channel amplifier and the operating bias voltage for the APD. The box itself has several functions, which include fiber alignment to the APD pixel array, light-tight connection to the scintillator module, removal of heat from the electronics and TEC, and protection from condensation. Secondly, a clamping frame is placed between the connector and FEB to provide the base support for the APD module. Before securing the module onto the frame, however, the optical connector must be thoroughly cleaned with isopropyl alcohol and have an o-ring placed in its groove. Additionally, the APD pixels must be given one last inspection before attachment to the optical connector. Third, the gas line from the neighboring APD must be connected to the free barb on the installed module while its own gas line is connected to the return line and checked for proper airflow. Fourth, the electrical connections are made with the APD ribbon cable going onto the FEB, as well as the temperature monitor, and the ground wire (Figure 12). After cataloging the APD's location in the database, the box cover is fastened over everything except the gas lines and the TEC water hoses. Lastly, the water lines are then connected to the water supply line and the neighboring APDs. The APDs are turned on in batches and run "warm" to verify that they are operational on the detector. Eventually they will be operated in a cold mode, using the water to remove heat via the TE coolers, so that the signal can be better detected over background noise.

4. Impact on Laboratory or National Missions

Neutrinos today are bringing exciting new theories that seek to answer profound questions that the Standard Model of Particle Physics could not address. The NOvA project intends to lead the charge into answering some of the basic fundamental questions regarding this elusive particle. NOvA will uphold the mission of Fermilab to advance the understanding of matter and energy to a greater degree as the team studies the nature of the neutrino. By providing passionate leadership, cutting-edge technology, and qualified researchers, NOvA will conduct research that, if successful, will revolutionize the frontiers of high-energy physics and maintain the United States' position as the foremost leader in scientific discovery and innovation.

In addition to fulfilling the goals of Fermilab and maintaining our high standing in high-energy and particle physics, there are additional benefits to the laboratory's scientific research. Though the common layperson may believe that endeavors such as the NOvA project are a waste of valuable tax dollars that provide no immediate impact on the lives of Americans, they do in fact improve our society. Unbeknownst to many people, innovations and investments in scientific research and technology are the catalysts for future economic growth. Tools developed for particle physics research have been repurposed or redesigned to improve our quality of life by shrinking tumors, disinfecting drinking water and surgical instruments, scanning the body to diagnose diseases, reducing nuclear waste, improving national security, running a search on Google, and much, much more. Such discoveries lead to new jobs, a higher quality of life, and societal progress. Most importantly, scientific research gives us a better understanding of who we are and how we came to be. The questions of "why are we here?" or "how does the world work?" have been in the thoughts of humankind and sparked our imagination since the beginning of recorded history. Neutrino research will continue that legacy. Take for example the Big Bang, which would have produced huge numbers of neutrinos. If they have mass, it is possible that the matter in the universe today arose because of the decay of neutrinos with non-zero mass during the early stages of the universe. All matter for which we are comprised may have arisen through this decay process. Therefore, we may be the product of neutrinos. That is an idea worth exploring.

5. Conclusion

The QA and installation processes can be time consuming. The supply of APD modules from assemblers in CalTech can be irregular due to delays. For Summer 2014, there was an average of one and a half weeks for APD shipments (one or two boxes each containing 24 APDs) to arrive at Fermilab. The QA process for one box can consume half of a day barring problems with testing equipment. When completed, nearly 35 percent of APD modules fail the QA process mostly due to vacuum and TEC test failures. As for installation, the process of putting a single APD in place and subsequent checks for gas leaks can be completed within 10 to 15 minutes. Completion of one row from a section of the near detector can take between four and five hours (32 APDs). Despite delays in delivery or protracted APD evaluations, the completion of the near detector is expected by the end of August 2014. In the end, our careful analysis of each photodetector ensures maximum performance of detecting neutrino interactions.

Acknowledgements

I would like to thank Mathew Muether and Xuebing Bu for their mentorship throughout the summer internship. Also, I am grateful for the assistance and generosity provided by Karen Kephart, who always kept her door open to anyone. In addition, I cannot afford to forget the invaluable assistance offered by the graduate students working on the NOvA project: Marco Colo, Stefano Tognini, and Tian Xin. Their expertise and company were absolutely appreciated. In addition, I thank Michelle Jonas and Tamara Hawke for their willingness to teach me the installation process. Lastly, Tanja Waltrip deserves a special thanks for her guidance of all interns and coordination of group talks designed to educate undergraduate students concerning the graduate school application process, interview process, and overview of potential careers. The funds for the summer internship were provided by the U.S. Department of Energy, Office of Science.

References

[1] Griffiths, David. *Introduction to Elementary Particles*. 2nd Ed. Wiley-VCH Verlag GmbH & Co., 2008.

[2] “The Reines-Cowan Experiments – Detecting the Poltergeist.” *Los Alamos Science.* 25 (1997): 4-27. Print.

[3] Raaf, Jennifer Lynne. *A Measurement of the Neutrino Neutral Current π^0 Cross Section at MiniBooNE.* Diss. University of Cincinnati, 2005. Print.

[4] “Project Poltergeist.” *Horizon*. BBC. 18 Mar. 2004.

[5] Ayres, D. S. et al. *Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\upsilon_\mu \rightarrow \upsilon_e$ Oscillations in the NuMI Beamline: NOvA.* Fermi National Accelerator Laboratory. 21 Mar. 2005.

[6] Fishburn, Matthew William. *Fundamentals of CMOS Single-Photon Avalanche Diodes.* 2012.

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Appendix

1: Participants

Name	Institution	Role
Xuebing Bu	Fermilab – Particle Physics Division – Intensity Frontier Department - NOvA	Co-mentor. Gave me my first tour of the near detector in the underground facility. Explained how the detector operated. Assisted with the setup of my NOvA computer account. Provided critiques and advice concerning my research paper.
Marco Colo	Fermilab – Particle Physics Division – Intensity Frontier Department	Provided QA and installation training.
Karen Kephart	Fermilab – Particle Physics Division	Selected me out of a pool of applicants for the 2014 summer internship. Provided counsel and attention to concerns.
Mathew Muether	Fermilab – Particle Physics Division – Intensity Frontier Department	Lead mentor. Explained the theoretical framework of behind the detector and how it detects neutrino interactions. Introduced the UNIX operating system and the program ROOT. Answered any question I had.
Stefano Tognini	Fermilab – Particle Physics Division – Intensity Frontier Department/Student	Introduced me to the QA process and explained the purpose for each step.
Tian Xin	Fermilab – Particle Physics Division – Intensity Frontier Department	Explained the first phase of the QA process. Taught me how to access the NOvA online database and produce noise plots from digital sampling oscilloscope (DSO) scans.

2: Data and Pictures

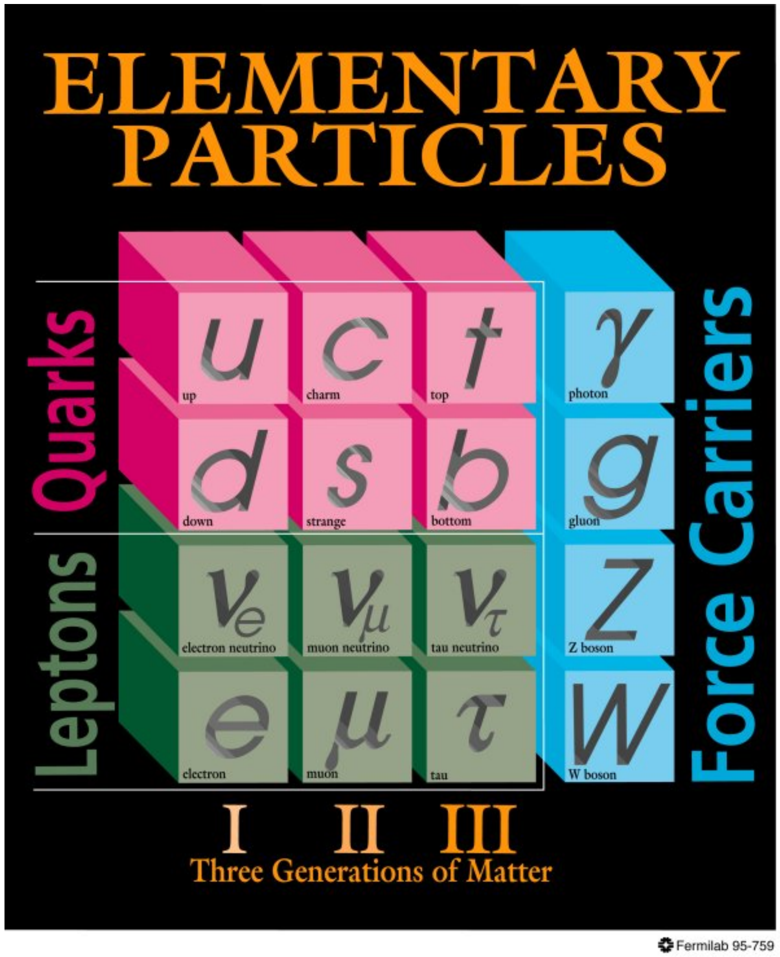


Figure 1: The Standard Model of Particle Physics.

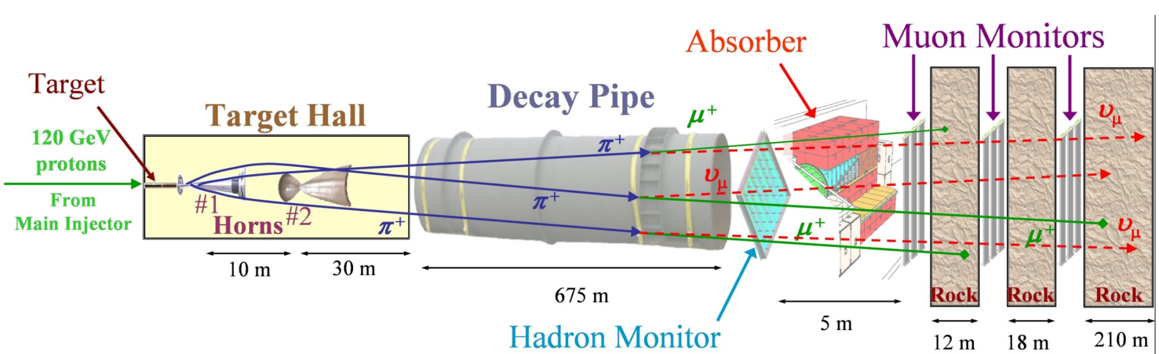


Figure 2: The NuMI Beam.

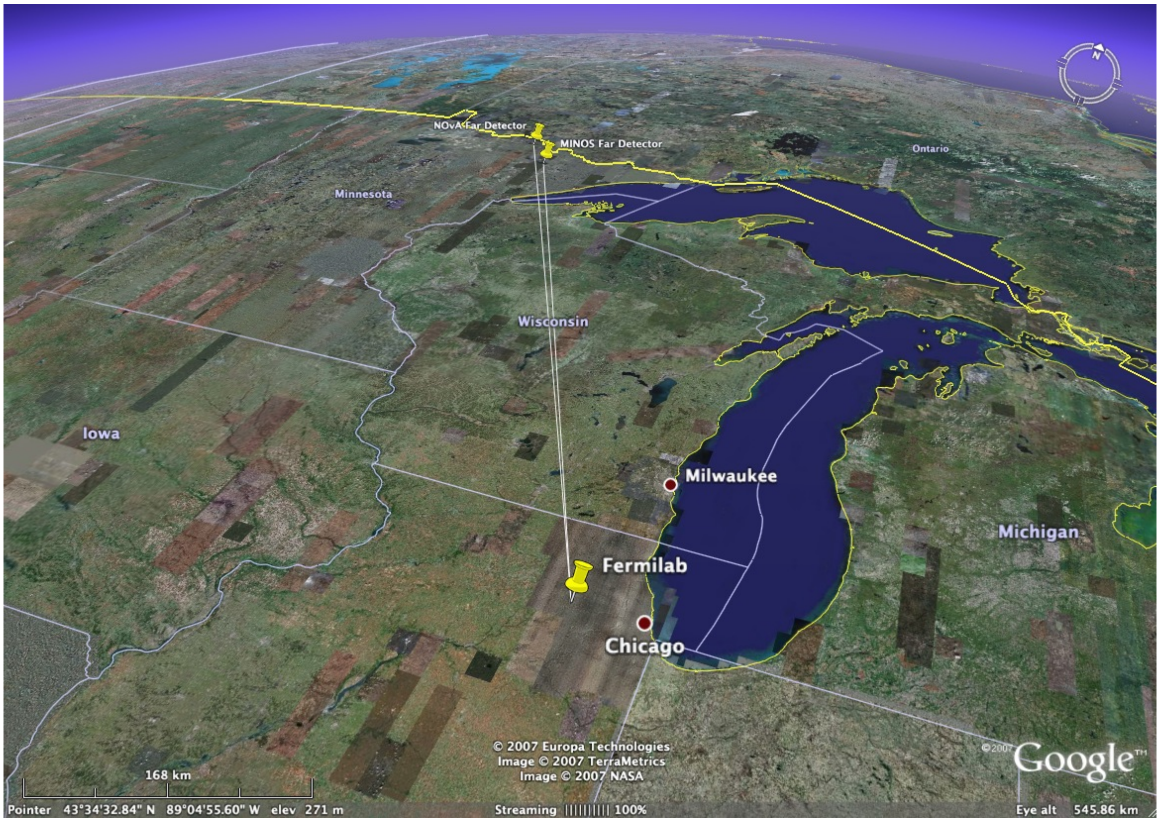


Figure 3: The near and far detectors are 810 km apart; farthest available site in the U.S. along the NuMI beam.

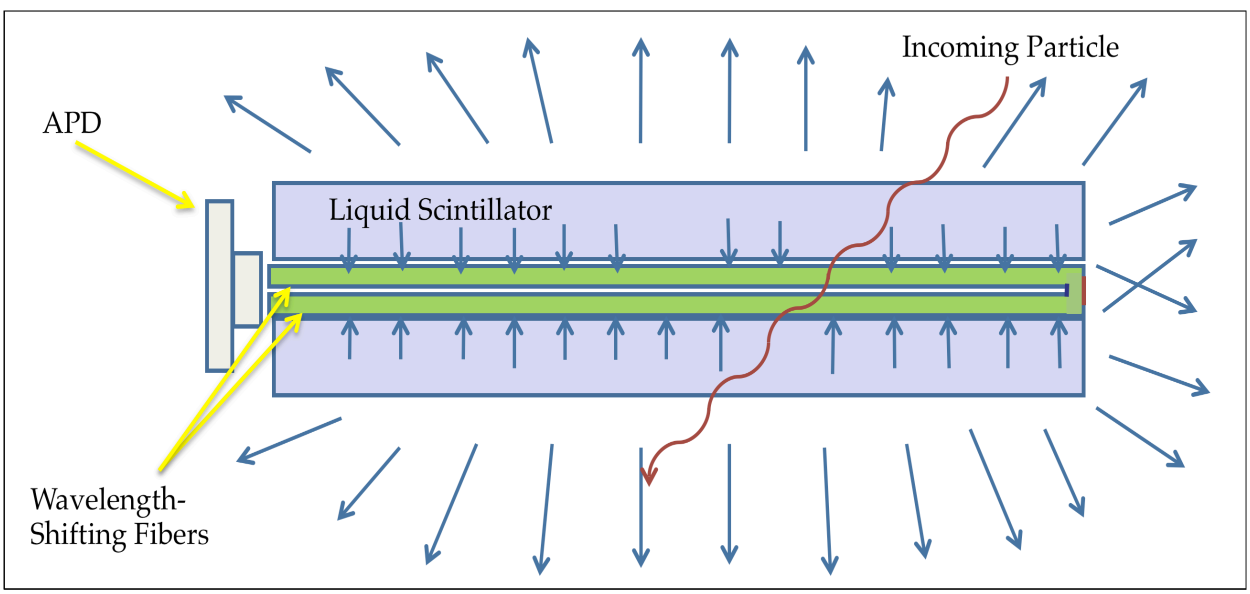


Figure 4: Diagram of a scintillator emitting light to a WLS fiber that is facing one APD pixel.

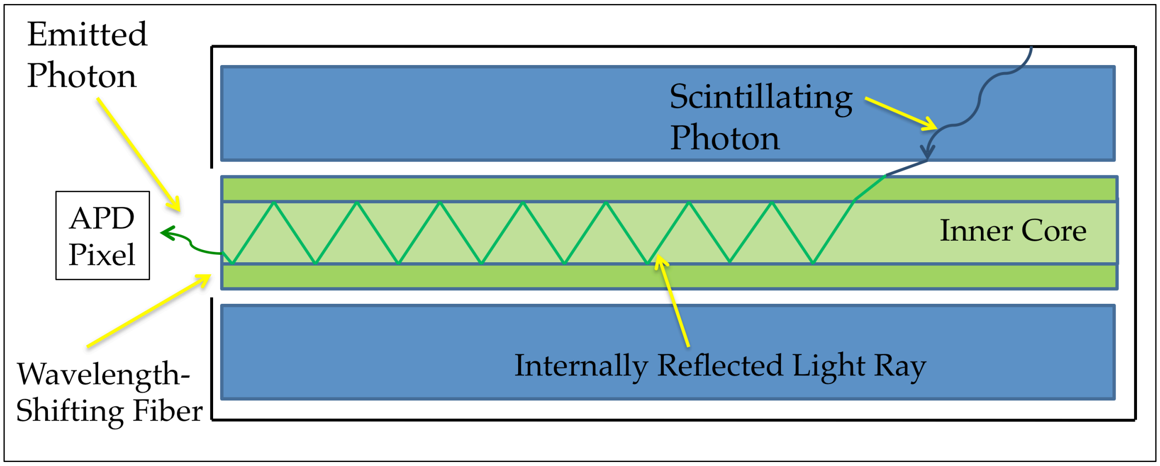


Figure 5: A wavelength shifting fiber catches blue light from the liquid scintillator, shifts that energy to green light, and transfers the light via *total internal reflection*.

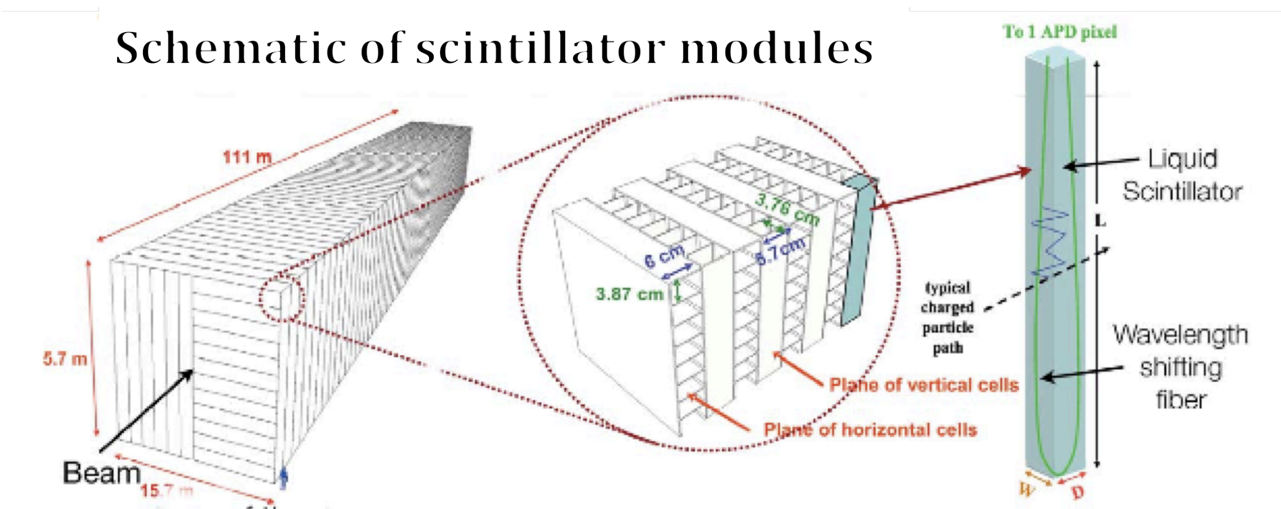


Figure 6: Diagram showing the horizontal and vertical planes of scintillator cells in the detectors.

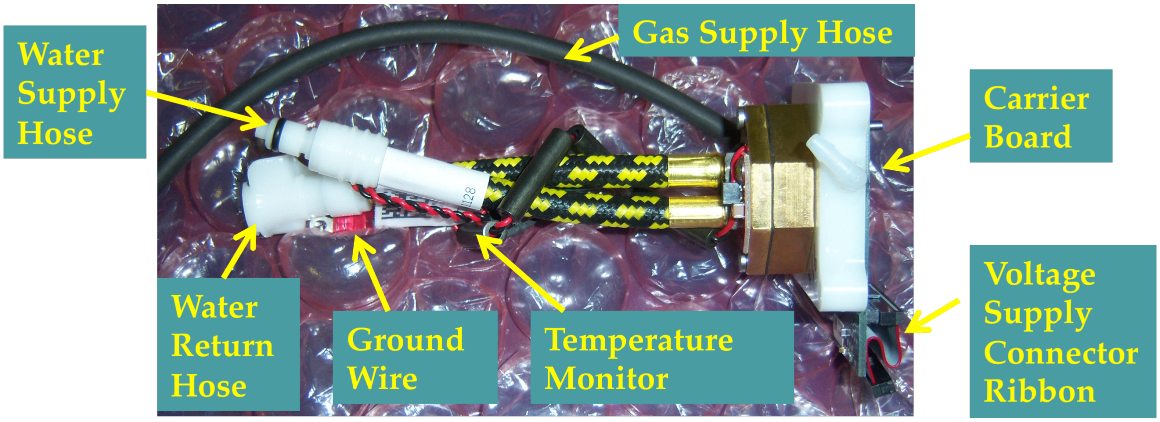


Figure 7: APD Module.

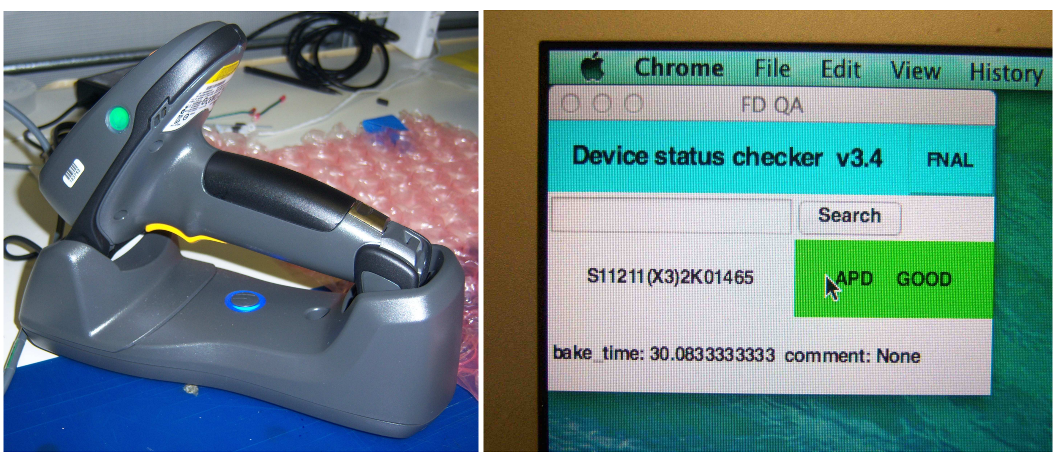
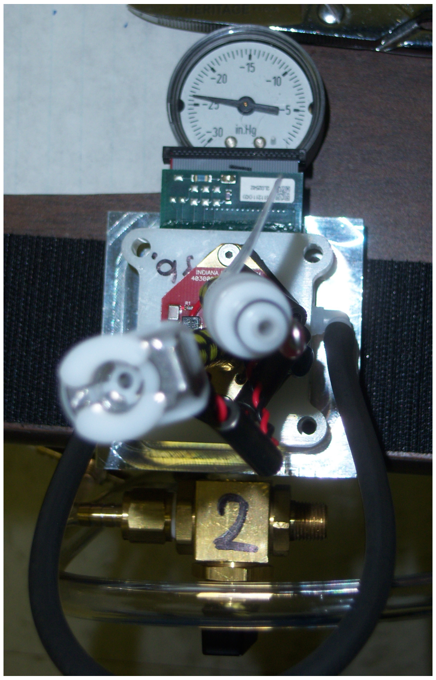
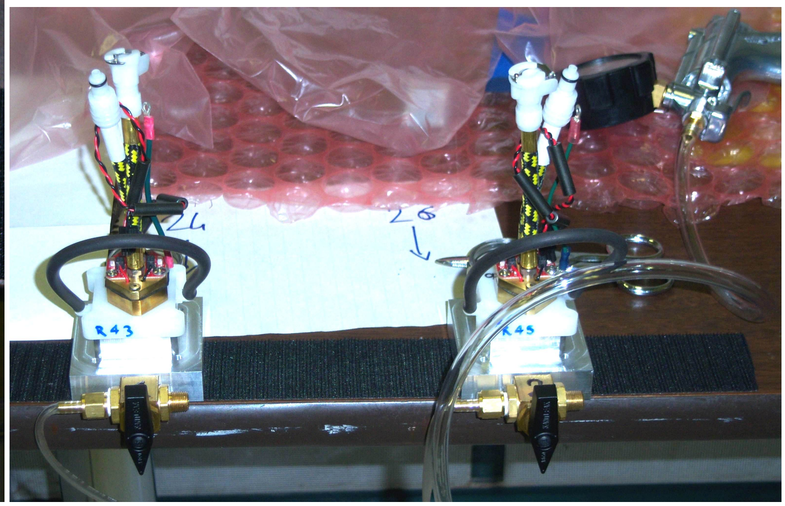
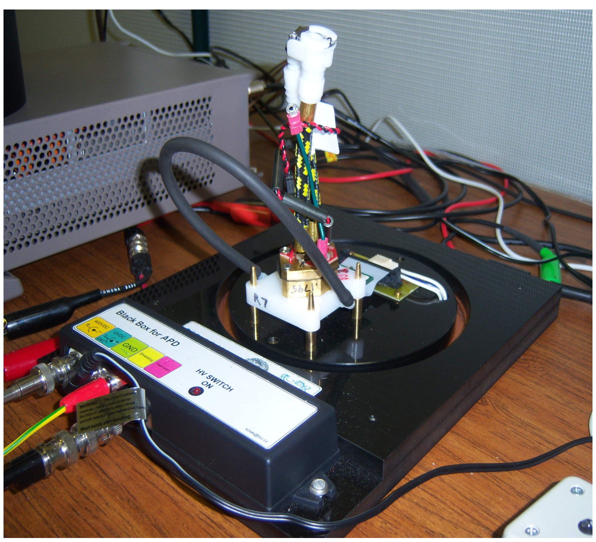


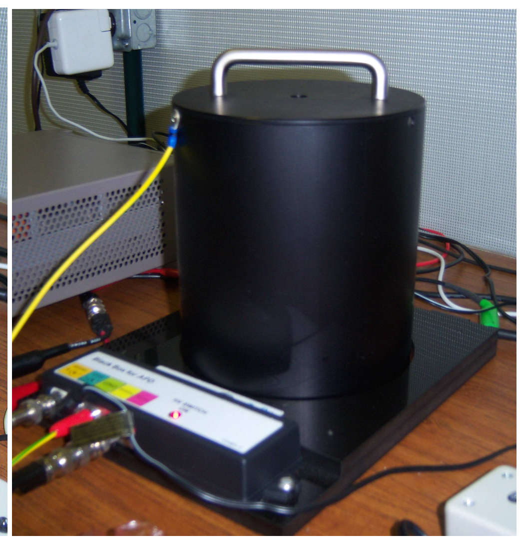
Figure 8: A barcode scanner is used to check the status of an APD.





Figures 9 and 10: APDs being vacuum tested.





Figures 10: The Black Box Test requires a cover to block out all light to test the APD's dark current.

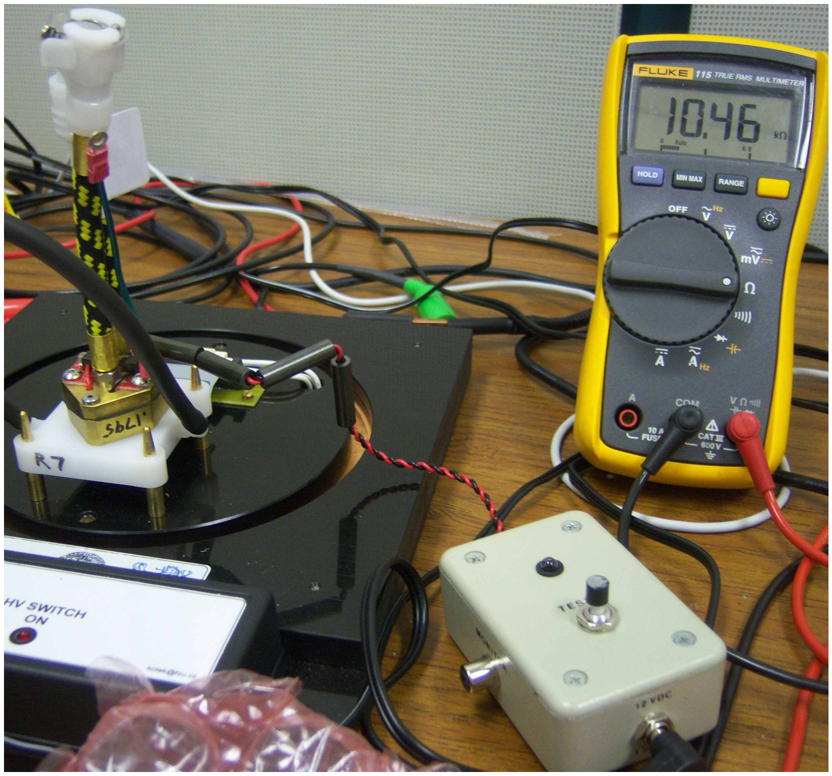


Figure 11: The thermo electric cooler (TEC) cools the APD so as to limit noise on the electronic readouts. We apply power and measure the resistance of the photodetector to see if heat is being transferred from the APD to a heat sink. The red and black cord is the temperature monitor.

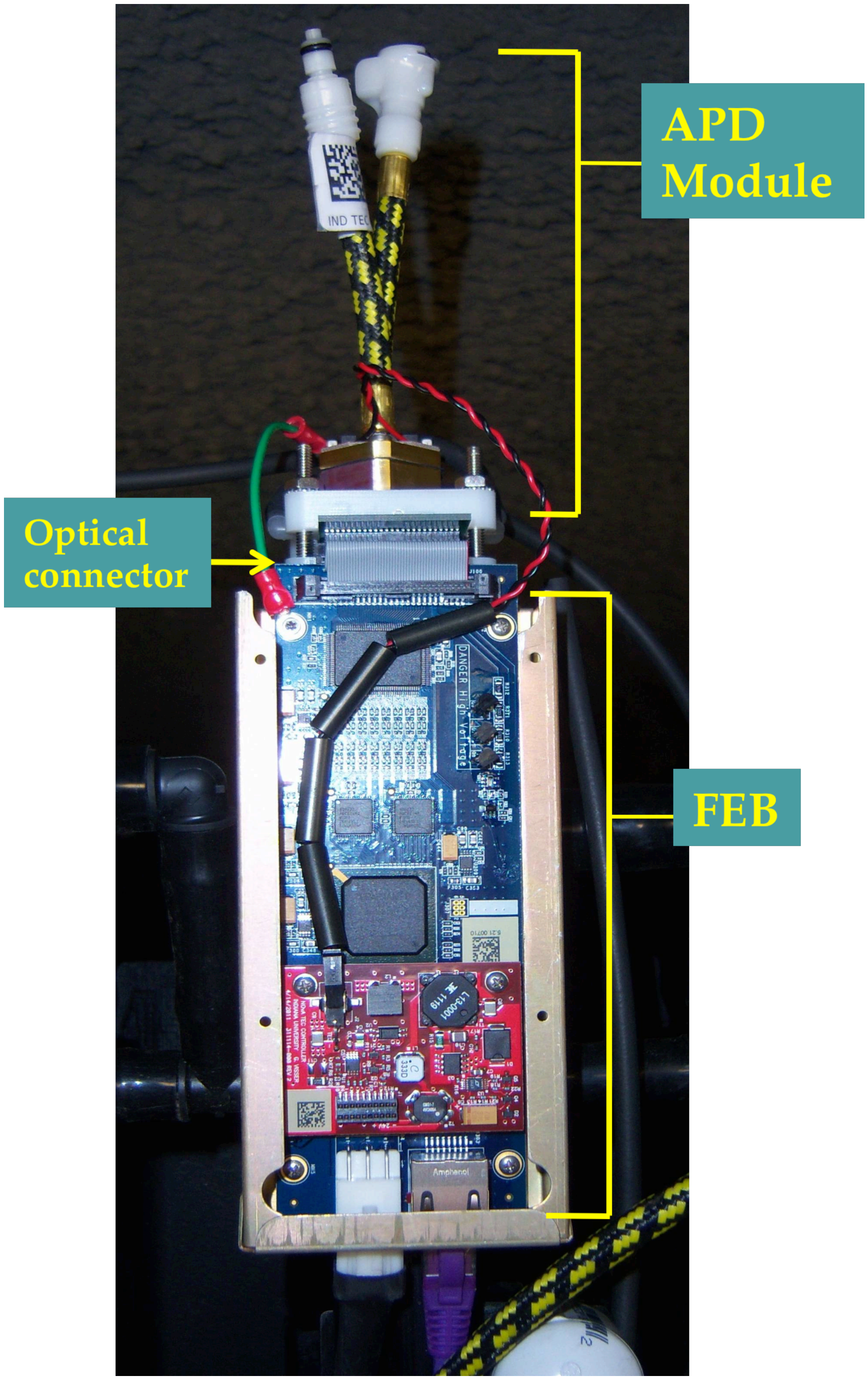


Figure 12: An APD module installed onto an optical connector attached to a front-end board.

Figure 13: A completed row on the near detector.

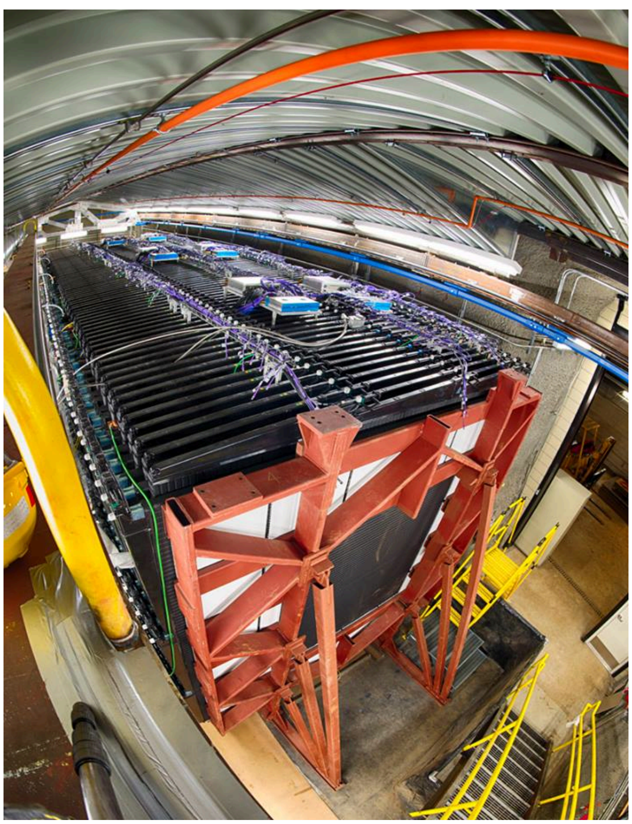


Figure 14: The NOvA near detector.