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Ajib Paudel

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Photon Detection System for DUNE Low-Energy Physics Study and the Demonstration of a Timing Resolution of a Few Nanoseconds Using ProtoDUNE-SP PDS †

Ajib Paudel on behalf of the DUNE Collaboration

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA; apaudel@fnal.gov

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Abstract: Photon detection systems (PDS) are an integral part of liquid-argon neutrino detectors. Besides providing the timing information for an event, which is necessary for reconstructing the drift coordinates of ionizing particle tracks, photon detectors can be effectively used for other purposes, including triggering events, background rejection, and calorimetric energy estimation. PDS in particular for the DUNE Far Detector Module 2 is designed to achieve a more extended optical coverage ($\rightarrow 4\pi$) with new-generation large-size PD modules based on the ARAPUCA technology. This will provide enhanced opportunities for the study of low-energy neutrino physics using PDS. The ARAPUCA technology was extensively tested within the ProtoDUNE-SP detector operated at the CERN neutrino platform. Here, we present a study of the timing resolution of ARAPUCA detectors using light emitted from a sample of energetic cosmic ray muons traveling parallel to the PDS. An intrinsic timing resolution in the order of 3 ns is observed for the ARAPUCA detectors. The excellent timing resolution ability of PDS can be exploited for further enhancing physics studies using the DUNE far detectors.

Keywords: ProtoDUNE-SP; ARAPUCA; DUNE FD2 PDS; power over fiber; signal over fiber

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1. Introduction

ProtoDUNE-SP [1] is a liquid-argon time projection chamber detector (LArTPC) built at the CERN neutrino platform, designed as a prototype for the far detector module of the next-generation neutrino oscillation experiment DUNE (Deep Underground Neutrino Experiment). A nominal electric field of 500 V/cm was used during its operation. At an electric field of 500 V/cm, liquid argon approximately emits 25,000 vacuum ultraviolet (VUV) photons per MeV of energy deposited by ionization in LAr [2]. A fraction of these photons are detected by photon detectors installed in ProtoDUNE-SP. The photon detectors are integrated into the anode plane assemblies (APAs), occupying the space between the two mesh planes. Ten bar-shaped photon detectors with a length of 2.2 m are embedded at equally spaced heights within each APA. A few different types of photon-detector technologies [1] were tested in the ProtoDUNE-SP detector, with silicon photo-multipliers (SiPMs) used to convert light to an electrical signal in each design. Figure 1 shows photon detectors embedded in APA6 of ProtoDUNE-SP. In the current analysis, we use data taken with ARAPUCA detector technology [3], in which light is collected at several positions along the bar. In the ARAPUCA design, photons are trapped inside a box with highly reflective internal surfaces, so that the detection efficiency of trapped photons is high even with a limited active coverage of its internal surface. Photons are trapped using a smart wave-shifting technique and the technology of dichroic short-pass optical filters [3].

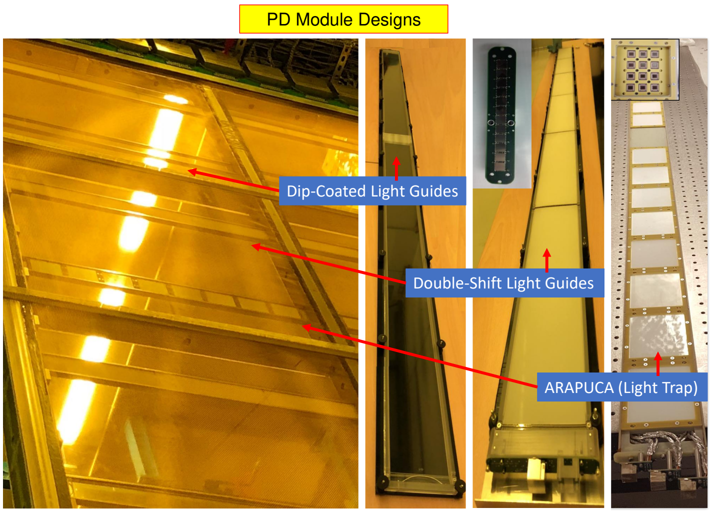


Figure 1. Photon detectors using different technology embedded in APA; the photodetector arrays are shown in the inserts. Figure taken from [1].

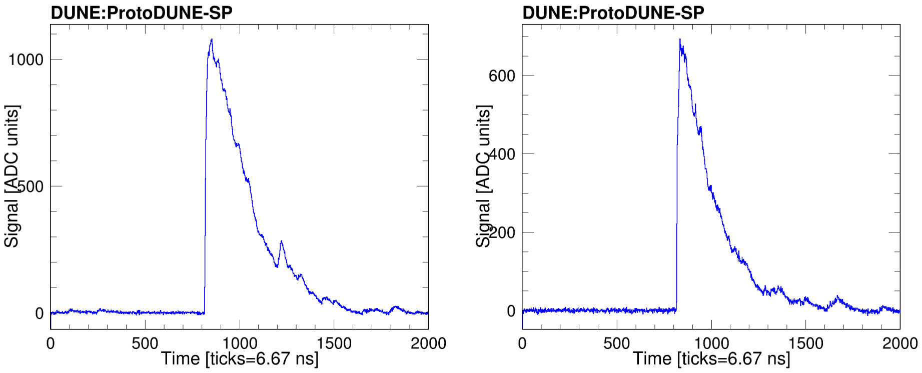
2. Materials and Methods

The ProtoDUNE-SP detector began operation in August 2018. Data were collected for around 600 days. During the data-collecting period, we collected both test beam and cosmic data. In the current analysis, we use cosmic-ray tagger (CRT)-tagged cosmic data taken in November 2018. The event selection is based on the simultaneous occurrence of flashes on the upstream and downstream CRT panels. Cosmic muon tracks near parallel to the ARAPUCA bars in APA6, Figure 1, are selected. Twelve ARAPUCA channels are spread over a distance of ∼2.3 m. The ARAPUCA detectors being near each other, the time of arrival of the first photon to each ARAPUCA cell should be nearly identical for each event.

Estimating the time of arrival of the first photon: PDS signals were read using an ADC digitizer with a sampling frequency of 150 MHz, which corresponds to a sampling time of 6.67 ns. The timing resolution can be affected by the sampling time. To minimize the effect of sampling time on the measured timing resolution, a fitting method was used to estimate the arrival times for the first photon. Figure 2 shows the waveforms observed by two distinct nearby ARAPUCA channels for the same cosmic muon event. The signals correspond to more than 50 photo-electrons (PEs). To estimate the arrival times for the first photon (t_0), we select 5 points near the rising edge of the waveform, as shown in Figure 3. The points are then fitted to a Gaussian distribution. The average amplitude for a single PE is known for each channel from the calibration data [1]. The time at which the signal crosses the amplitude of a single PE for that channel is the measured t_0. In the same way, the arrival time for the first photon to all the ARAPUCA channels can be measured.

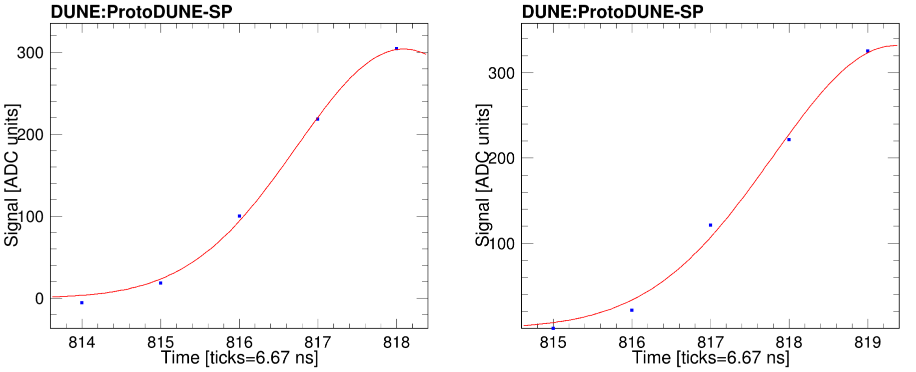
Measuring the timing resolution: Two channels close to each other are selected and the difference in time measured by the two channels for the same event is measured. Figure 4a shows the difference in time measured by two nearby channels. The width of the distribution is a measurement of the timing resolution of the detectors. There are 12 ARAPUCA channels in APA6, which makes 66 pairs. The timing resolution is measured for each pair of ARAPUCA channels. Figure 4b shows the timing resolution for all pairs of ARAPUCA detectors. An average timing resolution of 4.3 ns is observed.

Dependence of timing resolution on the number of photons detected: The data are divided into different samples based on the number of photons detected. The timing resolution is measured for each sample. Figure 5 shows the timing resolution as a function of the average number of photons. As the number of photons detected increases, timing resolution improves. At a sufficiently large number of photons, the timing resolution approaches a fixed value. The timing resolution at a sufficiently large number of photons gives the intrinsic resolution of the detectors, which is measured to be ∼3 ns.



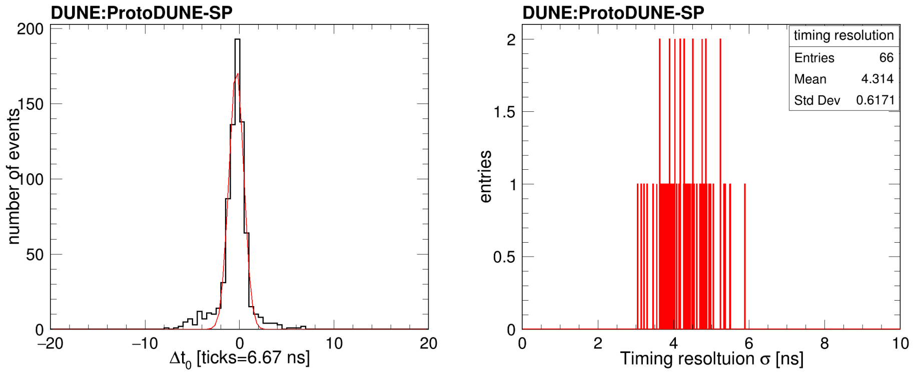
(**a**) (**b**)

Figure 2. Waveforms as seen by two different ARAPUCA channels (**a, b**) for the same cosmic muon event. Waveforms reprsent signal amplitude as a function of time.



(**a**) (**b**)

Figure 3. Blue markers: five points of the waveform near the rising edge of the signal for two nearby ARAPUCA channels (**a**,**b**); the first point is selected below the amplitude of a single photo-electron (SPE) and the remaining four points are selected above the amplitude SPE. Red line: fit of the waveform with Gaussian function. Using the fit, t_0 for a and b is measured to be 814.44 ticks and 815.03 ticks, respectively.



(**a**) (**b**)

Figure 4. (**a**) Difference in time measured by two different ARAPUCA channels. A timing resolution of 5.2 ns is determined from the fit (red line). (**b**) Timing resolution taking different pairs of ARAPUCA detectors.

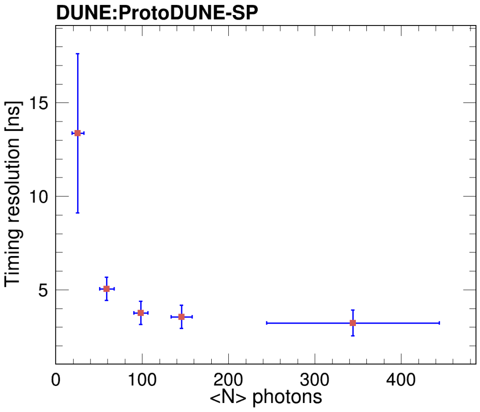
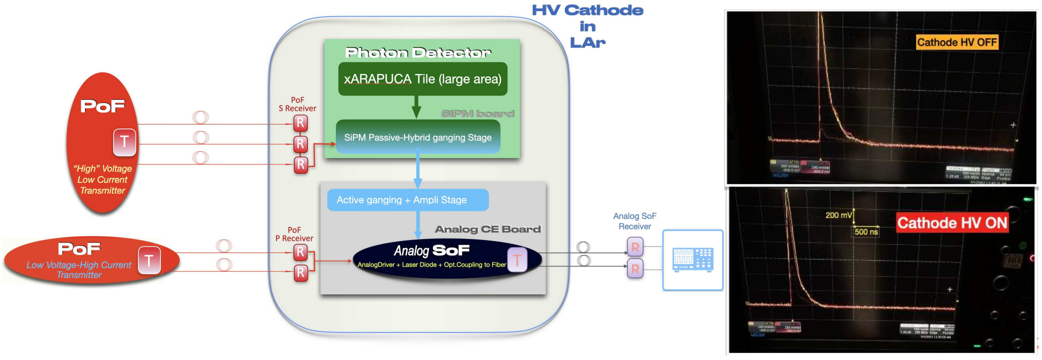


Figure 5. Timing resolution vs. average number of photons detected. Error bars indicate statistical variability, representing the standard deviations of the mean values.

3. DUNE Far Detector Module 2 PDS for Low-Energy Physics

In addition to providing the event time for drift coordinate measurements, PDS can be used for triggering, background rejection, and calorimetric energy reconstruction. One of the main goals of DUNE is to study supernova neutrino bursts [4]. The energy from supernova neutrino bursts is in the order of tens of MeV. TPC reconstructs them as small tracks or blips. At an energy of a few tens of MeV, the energy reconstruction ability of a TPC is not optimal. PDS can be used along with TPC in a calorimetric energy reconstruction system for DUNE, which will be specially useful at low energies. The simulation studies carried out for the DUNE far detector show that an increase in the light yield (number of photons captured per MeV or energy deposited) improves the energy resolution of the PDS [4]. In the quest for higher light yield, the photon detection system for DUNE Far Detector Module 2 is designed to have optimal coverage ($\rightarrow 4\ \pi$), with new-generation large-size PD modules based on the ARAPUCA technology. To achieve the goal of near $4\ \pi$ coverage, PDS modules will have to be placed on top of high-voltage cathode surfaces in addition to behind the semi-transparent field cage and using a reflective charge readout plane (CRP).

Operating the PDS on the cathode HV surface requires electrically isolating the photosensors and read-out electronics. Power for biasing the SiPMs (high voltage, low current) and the signal amplification board (low voltage, high current) has to be supplied using non-conductive cables (optical fibers). At the same time, output signal must be transmitted via non-conductive cables (optical fibers). Existing power-over-fiber (PoF) and signal-over-fiber (SoF—optolinks) technologies are commonly employed for voltage isolation between source/receiver and embedded electronics in high-voltage or high-noise environments. However, none of the commercially available technologies are rated to operate in the cold (at LAr temperature). A highly specialized R&D has been launched (mid March, 21) to customize off-the-shelf PoF and develop SoF technologies and to validate both for cold applications, including limitations imposed on power dissipation in LAr. The main components of an electrically isolated PDS for the DUNE FD2 VD module are schematically represented in the block diagram of Figure 6a. The technology has been successfully demonstrated in a small-scale prototype of DUNE FD2 at the CERN neutrino platform. Figure 6b shows the photon signals on a digital scope from an electrically isolated (by using PoF and SoF technology) PDS placed on the cathode surface.



(**a**) (**b**)

Figure 6. (**a**) The VD R&D path for an electrically isolated (only optically connected through fibers) low-noise photon detector concept. (**b**) The first signals seen on the digital scope when PoF was turned on for both the ON and OFF cathode HV modes. The figure is taken from [5].The tests were carried out at LAr temperature.

4. Results and Discussion

The ARAPUCA technology for light detection has been demonstrated to show a timing resolution as good as ∼3 ns. A precise timing resolution will enhance physics studies, including Michel electron tagging, besides providing background rejection. An enhanced version of ARAPUCA technology (X-ARAPUCA [6]) is planned to be used for the DUNE far detector. To use the detectors as a calorimetric tool, and improve the energy resolution, DUNE Far Detector Module 2 is designed to have nearly 4π coverage. The photon detectors are planned to be placed on top of a high-voltage cathode, electrically isolating the detector using PoF and SoF technology. Intense R&D activities are ongoing to further develop and test the technology with a larger-scale prototype (ProtoDUNE Vertical Drift), already in the installation phase at the CERN neutrino platform.

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Conflicts of Interest: The author declares no conflict of interest.

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