Light detection with power and signal transmission over fiber

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ABSTRACT: The Deep Underground Neutrino Experiment is a next generation long baseline (1300 km) neutrino oscillation experiment. The neutrino beam measurements will be performed by a near detector and far detector. The far detector will consist of four modules, installed 1.5 km deep underground, based on Liquid Argon Time Projection Chamber (LArTPC) technology to detect particles. The Vertical Drift (VD) LArTPC is a recent technology proposed by the DUNE collaboration for the second FD module. In VD, light collection will be optimized by embedding photon detectors within the LArTPC cathode, which is biased at \(-300\) kV. As a result, power must arrive to the Photon Detection System and signal must be transmitted via non-conductive material. The proposed solution is to use Power-over-Fiber and Signal-over-Fiber. An intense validation of the system is being performed by the collaboration at the CERN Neutrino Platform. The design of the system and the results of the validation collected over the first half of 2022 are presented here.

KEYWORDS: Optical detector readout concepts; Noble liquid detectors (scintillation, ionization, double-phase); Time projection Chambers (TPC)

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1 Introduction

The Deep Underground Neutrino Experiment (DUNE) [1] is a long baseline neutrino experiment with the primary goal of performing precise measurements of neutrino oscillation parameters, determining the neutrino mass hierarchy and the Charge-Parity violating phase in the lepton sector. The detector has also the capability to perform excellent supernova neutrino burst detection and to investigate proton decay. DUNE consists of a near and a far detector, the Near Detector [2] will be placed around 574 m from the neutrino beam generated at the Long-Baseline Neutrino Facility at the Fermi National Accelerator Laboratory (Fermilab). The Far Detector (FD) is located at the Sanford Underground Research Facility 1300 km away and around 1.5 km underground. The FD is divided in four modules of Liquid Argon Time Projection Chambers (LArTPC) [3] each with 17.5 kt in mass.

A LArTPC based on the Vertical Drift (VD) technology [4] is being developed by the collaboration since 2020 as the second FD module. In this design, electrons are drifted vertically towards the anodes on the top and bottom of the detector, while the cathode is placed horizontally in the middle. The drift distance of 6.5 m is achieved by biasing the cathode to $-300 \text{kV}$. Figure 1 shows the schematic of the $62 \times 15.1 \times 14 \text{ m}^3$ LArTPC, where the anodes consist of Charge-Readout Planes (CRP), formed by perforated printed circuit boards, to collect the drifting electrons. The photon detectors are x-Arapuca devices [5–8] and are placed inside the cathode. The power and analog readout of the Photon Detection System (PDS) must be done through non-conductive materials as the latter are in common with the $-300 \text{kV}$ bias. This work focuses in the Power and Signal over Fiber, the proposed solution for the VD light detection.
Figure 1. Schematic concept of the Vertical Drift module [4]. (Left) The Charge Readout Planes (CRP) (Anode) are at the top and bottom of the LArTPC at a distance of 6.5 m from the cathode. The Field Cage ensures uniform Electric Field. (Right) Photon Detection system, based on the x-Arapuca device [5–8], is installed at the cathode.

2 Photon detectors

The Photon Detection System of the DUNE’s second FD module will be based on the x-Arapuca technology: a light trapping device which uses a combination of wavelength shifters (WLS) and a dichroic filter to trap photons inside a highly reflective cavity and detect them with silicon photomultipliers (SiPM).

The schematic of a x-Arapuca tile is shown in figure 2(a). The device sizes are 60 × 60 × 2.5 cm$^3$. Two sets of 36 dichroic filters coated with evaporated para-Terphenyl (pTP) are placed on the top and bottom of the device. The pTP shifts the 128 nm LAr scintillation light to around 350 nm which is transmitted through the dichroic filter with efficiency >90%. Inside the device, a WLS plate of doped PMMA [9] converts the 350 nm photons to a wavelength around 430 nm. These photons are trapped inside the device due to total internal reflection and by reflection in the dichroic filter (efficiency >90%) until they are absorbed or detected by one of the 160 SiPMs.

Figure 2. (a) Schematic of the x-Arapuca tile. The wavelength shifter plate is surrounded by SiPMs and placed in between 2 × 36 coated dichroic filters. (b) Passive hybrid ganging scheme of the SiPM board. Bias voltage (DC) and signals (AC) are decoupled © 2022 IEEE. Reprinted, with permission, from [10].
The SiPMs are divided in two channels, with 80 SiPMs each. They are passively ganged in small groups of 20 SiPMs, in a hybrid configuration for biasing and signal readout, in parallel and series respectively, as shown in figure 2(b). The differential signal from anode and cathode are AC-coupled to the readout.

3 Cold electronics board

3.1 Signal over Fiber (SoF)

The analog signal transmission over fiber is the proposed solution to read out the light signals from the SiPMs through a non-conductive material. The technology is commonly applied in experiments and industry. However, no commercial solution exists that can function within cryogenic liquids so a custom-made cold electronics (CE) board has been developed [11].

The latest schematic version of the CE board is presented in figure 3. The electric power is given by the Power over Fiber (see section 3.2) to a low-dropout (LDO) regulator which outputs a stable $\sim 5.2$ V for the active components of the board and to the DC-DC converter. The DC-DC converts the low voltage to a high voltage and low current for the biasing of the SiPMs.

![Figure 3. Schematic of the CE board with the SiPM bias through DC-DC converters and SoF.](image)

The differential signal from the SiPMs goes through the first stage amplification with a gain $\sim 5$ and is converted to an unipolar signal at the second amplification stage with gain $\sim 2$ (resulting in a total gain about 20 times). The signal is passed to the third stage, a laser driver which controls the 1310 nm Fabry-Pérot diode laser current. The laser is kept with a constant offset, in order to be operated in the linear region. A set of resistors in parallel, with the use of a NTC thermistor allows the use of the CE board in cold and room temperature. The analog signal is transmitted through optical fibers to the warm receivers (Koheron PD100 units) to be converted to electrical signals again and read out by the DUNE data acquisition.

The PDS system has the requirement to operate with a Signal-to-Noise ratio (SNR) $>4$, a bandwidth of 30 MHz and a dynamic range of 1000 photo-electrons (p.e.), that is, to be able to detect up to 1000 photons. To accomplish these requirements, the Operational Amplifiers (OpAmps) were selected due to their high bandwidth (>150 MHz), low noise, being rail-to-rail...
and good performance in cryogenic temperatures [10, 11]. The gain of each OpAmp was set to compromise between the SNR and the bandwidth.

Currently, the following aspects of the PDS system are under development: a different amplification stage, with higher dynamic range and lower noise, by setting the third OpAmp as the laser driver without the need of the transistor; improvement in the laser-fiber interface to avoid loss when flooded by liquid argon; a custom made warm receiver which aims to integrate better with the front-end readout electronics of DUNE’s first FD module.

3.2 Power over Fiber (PoF)

The power supply of the SiPMs and the active components is given through fiber. The PoF system was completely developed at Fermilab. The current setup [10], uses Gallium Arsenide (GaAs) Photovoltaic Power Converters. Three GaAs receivers are mounted in the CE board in parallel, each receiver can output up to 7 V and a maximum current of ~80 mA. This configuration allows a higher current output for the active components and the DC-DC converter, which is around 100 mA. The GaAs was chosen due to the high (>50%) efficiency conversion even in liquid argon temperature (87.3 K). The light input is given by a Broadcom module with a +2 W capability 808 nm laser diode through standard multi-mode fiber link (62.5/125 μm).

4 System validation

The validation and integration of the system in liquid argon is done in the prototype called “Coldbox”, installed at the CERN Neutrino Platform. The LArTPC prototype is a $(3 \times 3 \times 1)$ m$^3$ cryostat, with 23 cm of drift distance between the anode and the cathode.

Figure 4 shows the coldbox’s cathode on the floor. The blue squares are two x-Arapuca devices installed on the cathode, while the green square are light diffusers of a UV LED flasher installed for calibration of the PDS. Finally, the red square is the area of the photon detectors, installed on the membrane (cryostat wall).

![Figure 4](image-url)

*Figure 4.* (Left) Cathode installed in the coldbox with two x-Arapucas (blue squares) using PoF and SoF, LED fiber output for calibration and photon detectors in the membrane for characterization of the system. (Right) Photo of the coldbox half filled with liquid argon. In this photo the CRP is not present.
The two large x-Arapucas (60 × 60 cm$^2$) nested in the cathode were installed with PoF and SoF. The system of the membrane consists of two small (12 × 12 cm$^2$) x-Arapuca devices and one large x-Arapuca device which are all powered through copper, while the signal is read out through SoF. The photon detection system on the wall helps to cross check the results and it allows for a comparison between powering by copper or fiber.

The data acquisition is done with CAEN Digitizer DT5730SB (14 bits, 2 V$_{pp}$ and 500 MSamples/s). The data were taken using three different trigger configurations: (1) a UV LED as external trigger for calibration of the SiPMs to retrieve the number of photo-electrons (p.e.) detected, (2) a self-trigger at different levels of signal (covering from 30 p.e. up to 100 p.e.) and (3) coincidence with a cosmic muon paddle telescope (CRT). Besides these three configurations, long (1 millisecond) waveforms are also taken with a random trigger for the study of the frequency response of the system.

In December 2021, the first signal transmission in liquid argon of a x-Arapuca device through fiber only was accomplished [10]. The device was successfully operated with cathode off and at −10 kV as shown in figure 5.

![Figure 5. Readout signals from the x-Arapuca operated with PoF and SoF without high voltage (left) and with a high voltage of −10 kV (right) © 2022 IEEE. Reprinted, with permission, from [10].](image)

The system was calibrated with the LED pulses, as shown in figure 6(a) where the spectrum of photo-electrons was retrieved with a Signal-to-Noise ratio of 4.9. The fit is performed with N + 1 Gaussian’s, with a baseline (no photo-electrons detected) and N peaks corresponding to N photo-electrons. The amplitude and standard deviation are left as free parameter for all Gaussians, however the mean $\mu_N$ of $N \geq 3$ Gaussians is kept fixed from the distance $\mu_2 - \mu_1$. The linear response of the detector was also studied and it is shown in figure 6(b) which shows the amplitude of the signals, in ADC channels, versus the average number of photo-electrons detected. The linear response of the device was proved up to ~300 p.e., in which the LED intensity was maximum [10].

\[\text{Signal-to-noise ratio defined as the average charge of one photo-electron divided by the standard deviation of the baseline charge (first peak of the histogram).}\]
Figure 6. (a) Single photo-electron spectrum obtained by flashing a UV LED with low intensity, the signals were readout through SoF and the SiPMs were biased by copper. (b) Linear response of the device as amplitude of the signals versus photo-electrons detected.

The PoF and SoF have been improved due to the tests at the coldbox. Besides the linearity study shown in this work, other measurements and analysis were done with the data, such as: verifying the effect of the electric field in the light yield of liquid argon [12], verifying the purity of the liquid argon through the triplet state component of scintillation, studying the light leakage of the infrared light in the system and studying noise level on the PDS system and CRP.

Multiple runs have been performed at the coldbox since December 2021, with several new developments and improvements. The proof of operation of the VD LArTPC photon detection system with power and signal over fiber has been demonstrated with a high voltage of $-10\text{ kV}$ through several tests.

5 Conclusion

For the first time, SiPM-based photon detectors (x-Arapucas) powered using PoF and read out with SoF has been operated at the CERN Neutrino Platform. In this work, we presented the performance of the SoF which resulted in a SNR $> 4$ which allows a precise calibration of the system. There are several ongoing research and development for all the instances of the vertical drift technology and the PDS has shown improvements since the beginning of the tests in 2021. The prototype of the second FD module is foreseen to be installed in the beginning of 2023 with many benefits from the coldbox tests.
References

[1] B. Abi, R. Acciarri, M.A. Acero, G. Adamov, D. Adams, M. Adinolfi et al., Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report Vol. I–IV (2020).

[2] A.A. Abud, B. Abi, R. Acciarri, M.A. Acero, G. Adamov, D. Adams et al., Deep Underground Neutrino Experiment (DUNE) near detector conceptual design report, Instruments 5 (2021) 31.

[3] T. Doke, Fundamental properties of liquid argon, krypton and xenon as radiation detector media, Portugal. Phys. 12 (1981) 9.

[4] DUNE collaboration, Far detector 2 — conceptual design report, in preparation (2022).

[5] A. Machado and E. Segreto, ARAPUCA a new device for liquid argon scintillation light detection, 2016 JINST 11 C02004.

[6] A. Machado, E. Segreto, D. Warner, A. Fauth, B. Gelli, R. Máximo et al., The X-ARAPUCA: an improvement of the ARAPUCA device, 2018 JINST 13 C04026.

[7] H.V. Souza, E. Segreto, A. Machado, R. Sarmento, M. Bazetto, L. Paulucci et al., Liquid argon characterization of the X-ARAPUCA with alpha particles, gamma rays and cosmic muons, 2021 JINST 16 P11002.

[8] L. Paulucci, The DUNE vertical drift photon detection system, 2022 JINST 17 C01067.

[9] C. Brizzolari, S. Brovelli, F. Bruni, P. Carniti, C. Cattadori, A. Falcone et al., Enhancement of the X-Arapuca photon detection device for the DUNE experiment, 2021 JINST 16 P09027.

[10] H. Vieira de Souza, A photon detection system with power and signal over fiber, 2022 IEEE 15th Workshop on Low Temperature Electronics (WOLTE) (2022), pp. 1–4.

[11] S. Sacerdoti, Development of analog signal transmission in LAr for DUNE, 2022 JINST 17 C01069.

[12] S. Amoruso, M. Antonello, P. Aprili, F. Arneodo, A. Badertscher, B. Baiboussin et al., Study of electron recombination in liquid argon with the ICARUS TPC, Nucl. Instrum. Meth. A 523 (2004) 275.