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The DUNE Far Detector Photon Detection System

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Abstract: The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline experiment for neutrino physics currently under construction in the US, aiming to measure neutrino oscillation parameters, search for beyond standard model physics and detect supernova neutrinos. DUNE will include a Near Detector (ND) and a Far Detector (FD), located 1300 km away from the ND and 1.5 km underground. The FD will consist of four 17-kton Liquid argon Time Projection Chambers (LArTPCs). In Phase I, two FD modules implementing horizontal (HD) and vertical (VD) drift technologies will be used. To test these technologies, two 750-ton LArTPCs (ProtoDUNEs) were built at CERN and were operated over the past two years.

In particular, the FD Photon Detection System (PDS) is critical for the DUNE physics program. The topology of a neutrino interaction in the LArTPC is reconstructed from the tracks of secondary charged particles, which produce scintillation light and ionization charge carriers during their propagation in LAr. The reference time of the event is provided by the scintillation light, detected by X-ARAPUCA modules, i.e. photon traps consisting of a box with highly reflective internal walls instrumented with an array of Silicon PhotoMultipliers (SiPMs).

In this paper, the designs of the DUNE PDS of the first two modules are presented, along with first results from ProtoDUNE-HD and ProtoDUNE-VD PDS operations. The preliminary results demonstrate the successful operation of the PDS, marking a crucial step toward validating the horizontal and vertical drift designs for the first FD modules.

Keywords: Cryogenic detectors; Neutrino detectors; Noble liquid detectors (scintillation, ionization, double-phase); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc)

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Contents

1 The Deep Underground Neutrino Experiment

The Deep Underground Neutrino Experiment (DUNE) is a next-generation international long-baseline neutrino experiment currently under construction in the United States [1]. The experiment will consist of two detectors exposed to an intense neutrino beam produced at the Fermi National Accelerator Laboratory (FNAL) in Illinois.

The neutrino beam, provided by the Long Baseline Neutrino Facility (LBNF) at FNAL, is designed to be the most intense in the world. The Near Detector (ND), located 574 m from the neutrino production point, is designed to characterize the unoscillated neutrino flux, perform neutrino-argon cross-section measurements, and constrain detector-related systematic uncertainties. The ND complex consists of three subsystems: ND-LAr, a modular Liquid Argon Time Projection Chamber (LArTPC) with a fiducial mass of about 50 t; the magnetized muon spectrometer TMS; and SAND, a magnetized on-axis beam monitor.

The Far Detector (FD) is located 1300 km from the ND and about 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota. It will consist of four LArTPC modules, enabling the detection of neutrino-argon interactions through the combined measurement of ionization charge and scintillation light.

The combined analysis of ND and FD data will allow precision measurements of neutrino oscillation probabilities as a function of energy, providing stringent constraints on the oscillation parameters. The primary physics goals include the determination of the CP-violating phase δ_{CP} in the leptonic sector, the resolution of the neutrino mass ordering, and the measurement of the octant of the mixing angle θ_{23}. In addition, DUNE will be sensitive to low-energy non-beam phenomena, such as neutrinos from core-collapse supernovae, and will probe physics Beyond the Standard Model, including baryon number violating processes like proton decay.

2 DUNE Far Detector

Each Far Detector (FD) module has an Liquid Argon (LAr) mass of at least 17 kt and an active volume of approximately $[14 \times 15 \times 62]\ \mathrm{m}^3$. The first two modules adopt two single-phase LArTPC designs, with all detector components immersed in LAr at 88 K, differing only in the orientation of the electric drift field.

The first module adopts a Vertical Drift (VD) configuration [2], where electrons drift vertically toward Charge Readout Planes (CRPs). This layout features two drift volumes with a maximum drift distance of 6.5 m, operated at an electric field of approximately 450 V/cm and requiring a cathode voltage of about −300 kV.

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The second module implements a Horizontal Drift (HD) configuration [3], in which ionization electrons drift toward Anode Plane Assemblies (APAs) hosting both charge readout and photon detection system. The detector is segmented into four drift volumes with a drift length of 3.5 m, operated at an electric field of about 500 V/cm, corresponding to a cathode voltage of −180 kV.

2.1 Far Detector Photon Detection System

The Photon Detection System (PDS) of the DUNE FD plays a crucial role in the reconstruction and identification of neutrino interactions. Its primary task is the measurement of the absolute start time of an event, which is required to determine the position of ionization signals along the drift direction in the LArTPC. In addition, the PDS contributes to improve energy reconstruction and provides the capability to trigger on non-beam events, such as neutrinos from core-collapse supernova bursts.

LAr is an excellent scintillation medium, producing approximately 25000 photons/MeV in presence of 500 V/cm electric field [3]. The scintillation light is emitted in the vacuum ultraviolet (VUV) range at 127 nm, with a fast (~7 ns) and a slow (~1.6 μs) component, and propagates efficiently thanks to the transparency of LAr to its own scintillation light.

To meet the requirements of VUV sensitivity (127 nm), cryogenic operation (88 K), and large-area coverage (partial coverage of the detector size, $[14 \times 15 \times 62]\ m^3$), the DUNE FD adopts the X-ARAPUCA technology, a light-trap device optimized for the collection of LAr scintillation photons [4]. The X-ARAPUCA uses a layered optical structure (figure 1) combining wavelength shifting and photon trapping: VUV photons are converted to 350 nm by a p-terphenyl (PTP) shifter, transmitted through a dichroic filter with a ~400 nm cutoff, and re-emitted at about 430 nm by a wavelength-shifting plate, with internal reflective surfaces enhancing photon confinement.

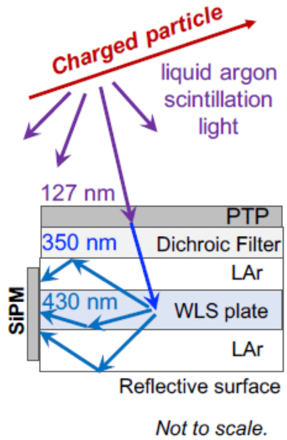

Figure 1. Schematic of X-ARAPUCA structure (not in scale). Reproduced from [3]. The Author(s). CC BY 4.0.

The X-ARAPUCA modules are equipped with Silicon PhotoMultipliers (SiPMs) [5]. To mitigate production risks, DUNE adopts a double-vendor strategy using customized devices from Fondazione Bruno Kessler (FBK, NUV-HD CRYO Triple Trench, 54 μm cell pitch) and Hamamatsu Photonics (HPK, S13360 HRQ, 75 μm cell pitch). Both SiPM types have a $6 \times 6\ mm^2$ active area and are optimized for cryogenic operation, providing high Photon Detection Efficiency (PDE) at 430 nm, gain above 10^6, and low dark count rates ($< 200\ mHz/mm^2$ at 3 V overvoltage in LAr). The overall PDE of the X-ARAPUCA system is of order 2%, making it a suitable solution for large-scale photon detection in the DUNE Far Detector.

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The layout of the PDS in the DUNE Far Detector depends on the drift configuration adopted for each module, as shown in figure 2. In the VD configuration, the PDS is based on large X-ARAPUCA MegaCells installed on both the cathode plane and the cryostat membrane walls. Each MegaCell hosts 160 ganged SiPMs, arranged in groups of 20 on flexible Kapton PCB strips, and is read out through two channels. A total of 352 MegaCells are mounted on the cryostat membrane walls behind the field cage, while 320 are installed on the cathode plane, where novel Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) solutions are implemented for SiPM biasing and signal readout [6, 7]. In the HD configuration, the PDS basic unit is the X-ARAPUCA SuperCell, instrumented with 48 electrically ganged SiPMs arranged in groups of six on eight mounting boards and read out as a single channel. Four SuperCells are combined into a Photon Detection (PD) module, with dimensions of approximately $[209 \times 12 \times 2]$ cm^3, and ten PD modules are installed within each APA, to provide distributed light collection.

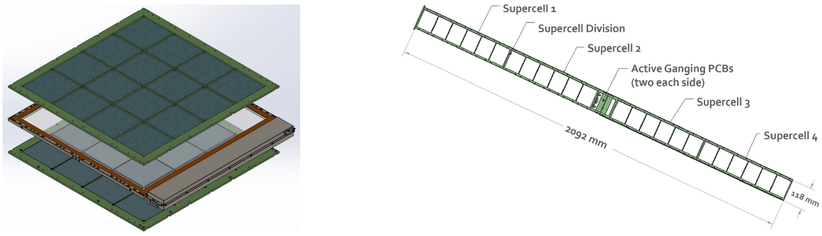

Figure 2. X-ARAPUCA MegaCells (on the left). Reproduced from [2]. The Author(s). CC BY 4.0. X-ARAPUCA SuperCell (on the right). Reproduced from [3]. The Author(s). CC BY 4.0.

3 ProtoDUNEs

The research and development activities, as well as the validation of the LArTPC technologies adopted for the first two DUNE FD modules, are carried out within the ProtoDUNE program at the CERN Neutrino Platform. This program provides large-scale prototype detectors that allow the testing of detector full-size components and system-level integration, acquiring beam, cosmic-ray, and calibration data. The ProtoDUNE detectors are hosted in two dedicated cryostats, NP04 and NP02. Following the operation of earlier single-phase and dual-phase prototypes, the current phase of the program focuses on two full-scale detectors implementing the VD and HD configurations, ProtoDUNE-VD and ProtoDUNE-HD, respectively.

3.1 ProtoDUNE-VD

ProtoDUNE-VD is a 750-ton LArTPC-VD with two 3.5 m drift volumes, operating in the NP02 cryostat from May 2025. It incorporates full-size detector components, including 4 CRPs, 8 cathode MegaCells, and 8 membrane MegaCells, and tests two X-ARAPUCA configurations combining FBK and HPK SiPMs with a Glass to Power WLS plate [2]. Commissioning and calibration were performed from May to August 2025, with periodic checks to monitor stability of the main PDS parameters, such as gain, signal to noise ratio (SNR) and single photoelectron (SPE) amplitude. Three beam periods were recorded over six weeks in Summer 2025, followed by pulsed neutron source calibration (January–February 2026) and PDS performance studies with Xenon doping (March–April 2026). Analysis of calibration, cosmic rays and beam data is ongoing and shows reasonable results in agreement with DUNE collaboration requirements.

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3.2 ProtoDUNE-HD

ProtoDUNE-HD is a 750-ton LArTPC, including four APAs and 160 X-ARAPUCA SuperCells. Four different X-ARAPUCA configurations were tested, combining two wavelength-shifting plates (Eljen and Glass to Power) with the two selected SiPM models. It operated in the NP04 cryostat at CERN during 2024 and was exposed to charged-particle beams for about ten weeks.

Several analyses were performed to characterize the ProtoDUNE-HD PDS performance. The SiPM Breakdown Voltage (V_{bd}) was monitored through dedicated IV curve measurements and results show time stability at the level of 2% and good agreement with previous laboratory results performed in liquid nitrogen, as shown in figure 3 [8]. Dedicated LED calibration runs acquired at different SiPM overvoltages were used to extract gain, signal-to-noise ratio, and single photoelectron response, which showed good time stability too, as shown in figure 4. In addition, other studies, as those shown in figure 5, were performed, about the dependence of the light yield on the electric drift field, which show the expected attenuation with increasing field in agreement with literature [9], and the scintillation light time profile from which the slow decay time component (tau slow, τ_{slow}) was extrapolated, showing a dependence on the electric field.

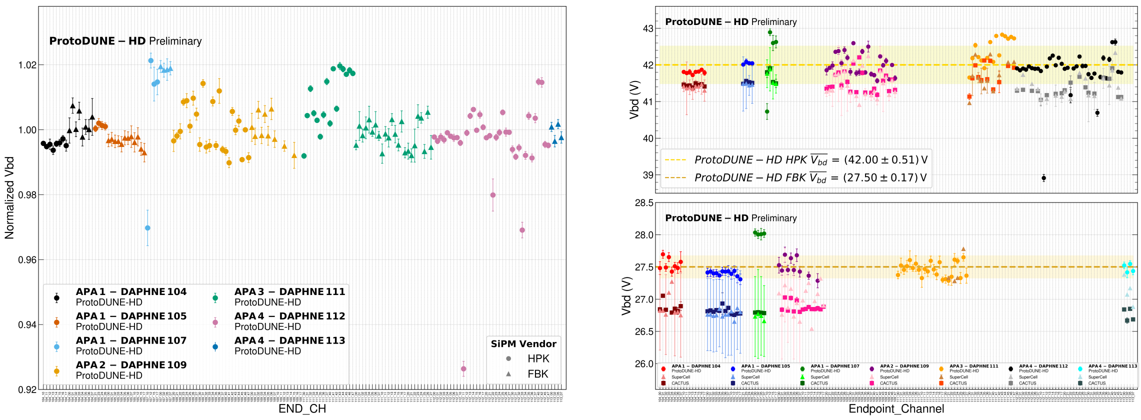

Figure 3. Breakdown voltage analysis: time stability (on the left) and comparison with laboratory measurements of single SiPMs (CACTUS data) and on whole SuperCells (on the right). Reproduced from [8]. CC BY 4.0.

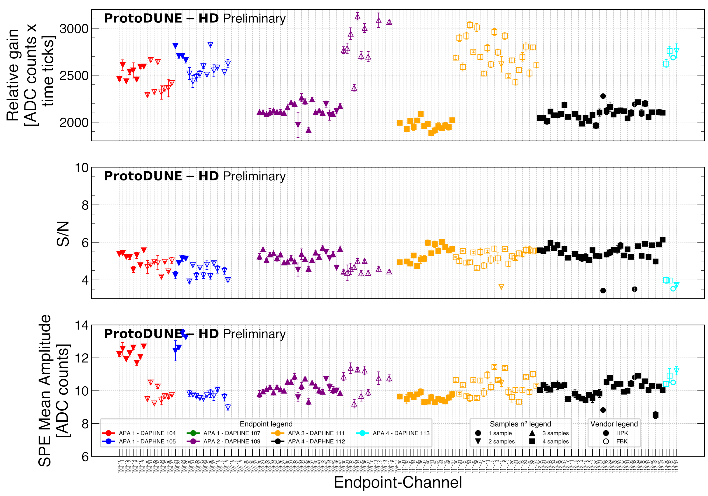

Figure 4. Gain, signal-to-noise ratio, and single photoelectron response time stability.

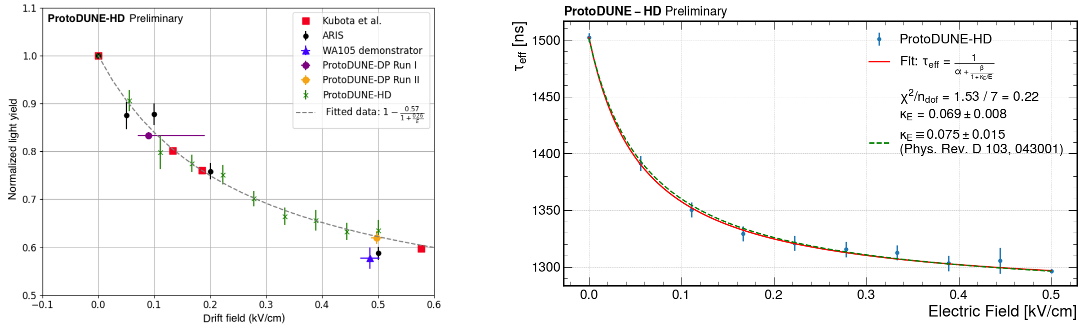

Figure 5. Light yield (on the left) and tau slow (on the right) as function of electric drift field.

References

[1] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I Introduction to DUNE*, 2020 *JINST* **15** T08008 [arXiv:2002.02967].

[2] DUNE collaboration, *The DUNE Far Detector Vertical Drift Technology. Technical Design Report*, 2024 *JINST* **19** T08004 [arXiv:2312.03130].

[3] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology*, 2020 *JINST* **15** T08010 [arXiv:2002.03010].

[4] A.A. Machado et al., *The X-ARAPUCA: An improvement of the ARAPUCA device*, 2018 *JINST* **13** C04026 [arXiv:1804.01407].

[5] S. Gundacker and A. Heering, *The silicon-photomultiplier: fundamentals and applications of a modern solid-state photon detector*, *Phys. Med. Biol.* **65** (2020) 17TR01.

[6] M.A. Arroyave et al., *Characterization and novel application of power over fiber for electronics in a harsh environment*, 2024 *JINST* **19** P10019 [arXiv:2405.16816].

[7] S. Sacerdoti, *Signal and Power transmission over Fiber in the DUNE Far Detector*, in the proceedings of the *25th International Workshop on Neutrinos from Accelerators*, Lemont, IL, U.S.A. (2024) [arXiv:2412.10177].

[8] A. Balboni, *ProtoDUNE-HD Photon Detection System performances: SiPM breakdown voltage*, *Nuovo Cim. C* **49** (2026) 83.

[9] B. Aimard et al., *Study of scintillation light collection, production and propagation in a 4 tonne dual-phase LArTPC*, 2021 *JINST* **16** P03007 [arXiv:2010.08370].

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