PROCEEDINGS OF SCIENCE

The DUNE Photon Detection System

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The DUNE experiment, currently under construction in the US, has a broad physics program that spans from oscillation physics at the GeV scale to the observation of solar neutrinos in few-MeV events. This program leverages the unprecedented resolution and imaging capability of the liquid argon TPC. LArTPCs are dense, fully-active detectors, that allow for a 3D real-time reconstruction of the events, achieved by means of the collection of drifted electrons from ionization. In addition to electrons, LArTPCs produce large quantities of VUV photons, which will be fully exploited in DUNE thanks to its Photon Detection System (PDS). The light collected by the PDS will be of paramount importance to measure the event timing and the vertical trajectory of charged particles for non-beam events, and will improve significantly the overall energy resolution of DUNE, especially at low energies, allowing to unlock its full scientific potential. The last few years marked important steps in the development of the PDS. Thanks to an intense R&D effort conducted at the two ProtoDUNE detectors at CERN, the PDS technology for DUNE has been optimized and validated for the DUNE physics. This article illustrates the concept of the DUNE PDS, its development and use in ProtoDUNE, as well as its role in achieving the physics goals of DUNE.

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1. Introduction

The Deep-Underground Neutrino Experiment (DUNE) is a prominent endeavor in the field of particle physics. It is characterized by a large mass, high precision, and a deep-underground location, making it an ideal platform for studying neutrinos and other fundamental particles. In this article, we delve into the crucial role played by the DUNE Photon Detection System (PDS) in enhancing the experiment's physics capabilities.

2. DUNE Overview

DUNE is designed around a powerful wide-band neutrino (ν) and anti-neutrino ($\bar{\nu}$) beam, driven by a 1.2 MW proton beam that can be upgraded to 2.4 MW. This beam is complemented by a near detector complex, featuring both movable (NDLAr, TMS) and on-axis (SAND) detectors. However, the heart of the experiment lies in its massive far detector, consisting of four 17-kiloton Liquid Argon Time Projection Chambers (LArTPCs) situated 1.5 kilometers underground. This setup forms the basis for a wide-ranging physics program [1], that encompass several critical areas:

- the discovery of missing parameters in the lepton Yukawa sector, this includes determining the neutrino mass ordering and the measurement of the CP-violating phase δ_{CP};
- precise measurements of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) parameters, including the octant of $\theta 23$, Δm^2_{13}, and also of δ_{CP};
- the exploration of physics using natural neutrino sources, such as the first observation of HEP solar neutrinos, galactic Supernova (SN) bursts, and the best measurement of θ_{12};
- the investigation of several beyond the Standard Model (BSM) physics scenarios, including addressing neutrino anomalies at the Long-Baseline Neutrino Facility (LBNF), probing proton decay, and exploring dark matter.

Central to the success of DUNE is the LArTPC technology, which enables precise imaging through drifted electrons and accurate event timing via VUV scintillation photons. These two signals are crucial for understanding particle interactions, and are recorded by the a charge collecting system and a photon detection system (PDS) respectively.

3. LAr VUV Light Detection and Simulation

The detection of VUV scintillation light in LAr is made possible through various luminescence mechanisms, including recombination and self-trapped excitation. The optput consists of a fast ($\tau = 7$ ns) and a slow ($\tau = 1.6\mu$s) component, both caracterized by a wavelength of 128 nm. This light has several critical characteristics:

- abundance (25,000 photons/MeV at 500 V/cm) enhances calorimetry, especially at low energies;
- fast component ($\tau = 7$ ns) provides event timing, crucial for triggering non-beam events;

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- topological properties offer background rejection capabilities.

Detection of this light involves converting VUV photons to longer wavelengths using photofluorescent compounds (WLS) and conveying a fraction of it to silicon photomultipliers (SiPMs).

Simulating light in a LArTPC is crucial for understanding photon behavior and optimizing photon detection systems in experiments like DUNE. It involves three steps:

1. production - scintillation photons are generated when charged particles deposit energy in the liquid argon, with their characteristics depending on particle energy and electric field strength [2];

2. propagation - light propagation is simulated using efficient methods like voxelization and semi-analytic models, which predict photon positions without tracking each individually [3];

3. digitalization - scintillation photons are converted into waveforms that mimic real measurements, enabling accurate timing and energy information for event reconstruction.

4. The PDS of ProtoDUNE-HD and FD-I

The ProtoDUNE-SP, the largest LArTPC to date, was constructed to address technological challenges and validate DUNE specifications for the first far detector (FD-I). It successfully collected cosmic and test beam data at the CERN Neutrino Platform from 2018 to 2020 [4]. This prototype met or exceeded all DUNE specifications. The ProtoDUNE-SP's Photon Detection System (PDS) underwent rigorous testing, with three design options explored for 60 PDS modules: dip-coated light guides, double-shift light guides, and the ARAPUCA light trap (Fig. 1). Notably, the modules based on the ARAPUCA technology excellent performance (Fig. 2) in terms of timing ($\sigma t = 14ns$) and calorimetry (1.9 photon/MeV light yield). The ARAPUCA is now the preferred choice for DUNE's far detectors.

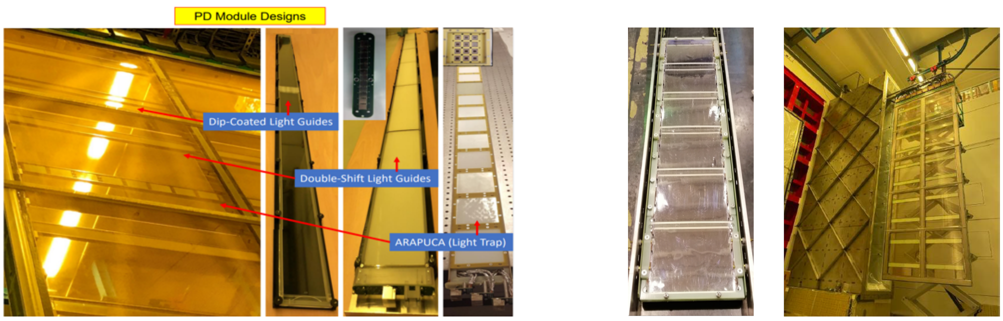

Figure 1: Photon Detection System of the ProtoDUNE-SP, with the three types of modules (left); and X-ARAPUCA modules of the ProdoDUNE-HD alone and embedded in the anodic planes as supercells (right).

In early 2024, ProtoDUNE-SP is set to undergo its second run, known as ProtoDUNE-HD or Module-0. This phase aims to validate recent R&D developments, including the introduction of the new X-ARAPUCA design [5]. The X-ARAPUCA design offers a compact form factor, a reduced number of channels, and an impressive photon detection efficiency (PDE) of $2-3\%$. For ProtoDUNE-HD, the active ganging of 48 SiPMs was achieved in a single readout channel, or

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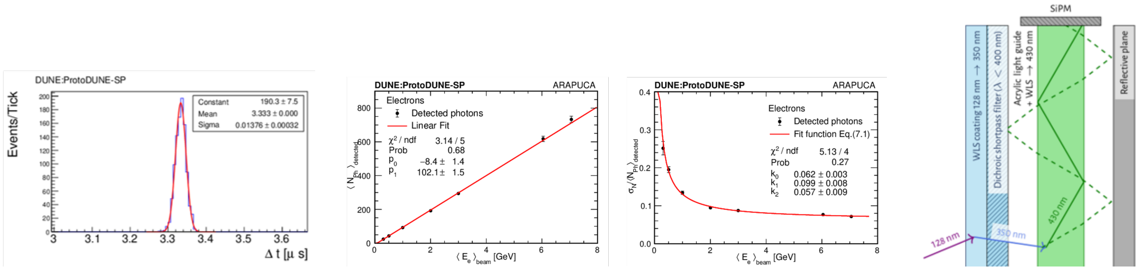

Figure 2: Performances of the ARAPUCA modules in terms of time resolution (left) and calorimetry (center); schematic repesentation of the X-ARAPUCA (right).

supercell. Four distinct configurations were employed, utilizing wavelength-shifting guides from Glass To Power (PMMA-based) and Eljen (PVT-based), combined with HPK-DUNE-75μm-HQR and FBK-TripleTrench SiPM models. In all configurations, $7.7 \times 10\,\mathrm{cm}^2$ OPTO-Campinas dichroic filters with B270 substrates were utilized. These efforts represent significant strides toward the mass production of this technology for implementation in the DUNE FD-I.

5. The DUNE Photosensors

SiPMs (Single-Photon Avalanche Photodiodes) are the photosensors of choice for DUNE due to their robustness, high sensitivity, and dynamic range [6]. Specific SiPM requirements for DUNE include quantum efficiency, dimensions compatible with ARAPUCA design, dynamic range, low dark count rate, and cryoreliability. Extensive testing of SiPM models from two vendors (Hamamatsu Photonics and Fondazione Bruno Kessler) was conducted, with downselection based on multiple parameters such as breackdown voltage V_{bd}, dark count rate, after pulse and cross-talk, gain and signal to noise ratio [7, 8] (Fig. 3). The chosen models for FD-I are the HPK-S16517 and the FBK-NUV-HD-CryoTT. Mass testing facilities have been established in five different institutes across europe to test all 300,000 FD-I SiPMs, ensuring quality and reliability, and allowing to gang SiPMs with similar V_{bd}.

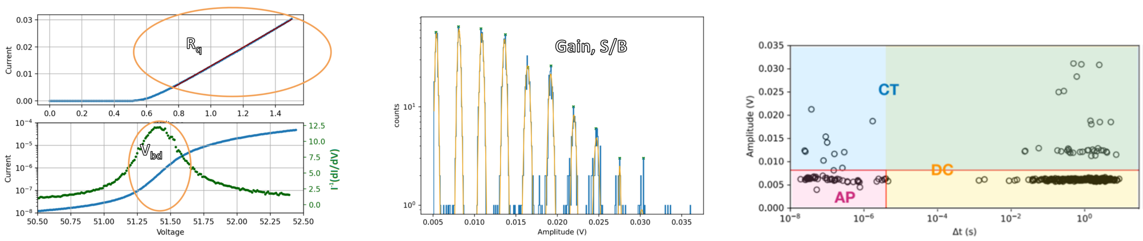

Figure 3: Examples of the results of the tests performed on the DUNE SiPMs: the quenching resistance R_q and breakdown voltage V_{bd} are extracted from the IV curves in forward and reverse polarization respectively; the gain and signal over background ratio are obtained from the histogram of event apmlitude; and the amplitude vs Δt plot gives the number of dark count, after pulse, and cross-talk events.

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6. The PDS of ProtoDUNE-VD, FD-II, and future modules

DUNE's second prototype and far detector (FD-II) utilize the Vertical Drift technology, capitalizing on the achievements of the dual-phase LArTPC R&D. This technology features a doubled drift length, vertical drift with a central cathode, and cold electronics with PCB readout. The PDS modules are placed in the cathode and outside the field cage, and light uniformity is improved with Xenon doping of LAr, which shifts the wavelength from 128 nm to 178 nm [9]. This approach has shown promise in ProtoDUNE-SP in recovering lost light due to nitrogen (N2) contamination and providing a faster and more uniform light signal, since a longer wavelength is less affected by Rayleigh scattering [10]. For the VD X-ARAPUCA modules, significant R&D efforts were dedicated to defining the design for FD-II. While they share the same technology as the HD modules, they differ in SiPM coverage and wavelength-shifting plate dimensions ($60.7 \times 60.7\text{cm}^2$), maximizing photon detection and active area. Recent measurements of photon detection efficiency (PDE) using a dedicated setup have yielded results similar to those of the HD modules ($\sim 2\%$). ProtoDUNE-VD also addresses the challenge of powering and reading SiPMs in the 300 kV electric field of the cathode, by implementing Power over Fiber (PoF) technology (Fig. 4). This innovative approach uses GaAs lasers and optical fibers to convert power to DC at cold temperatures, achieving good performance and durability.

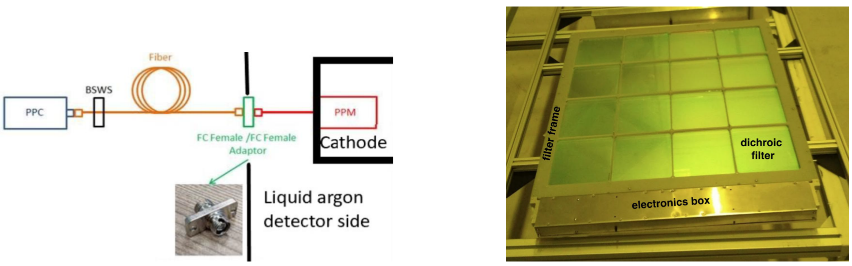

Figure 4: Schematic view of the power over fiber (PoF) system (left); and a VD X-ARAPUCA module (right).

DUNE's low-energy physics program heavily relies on light detection for trigger, particle identification (PID), and calorimetry, especially for low-energy electromagnetic showers [11]. Future modules, namely modules 3 and 4, are expected to expand the low-energy physics program. This expansion is contingent on an enhanced PDS that offers a lower threshold and improved background rejection capabilities.

7. Conclusions

In conclusion, the collection of VUV LAr scintillation photons is integral to the LArTPC technology used in DUNE. The successful testing and development of the Photon Detection System (PDS) technologies, particularly the ARAPUCA design, are expected to significantly enhance DUNE's diverse physics program. These advancements underscore the collaborative efforts and technological innovations that drive the success of the Deep-Underground Neutrino Experiment.

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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, volume ii: Dune physics*, *arXiv preprint arXiv:2002.03005* (2020) .

[2] F. Marinho, L. Paulucci, D. Totani and F. Cavanna, *Larql: a phenomenological model for treating light and charge generation in liquid argon*, *Journal of Instrumentation* **17** (2022) C07009.

[3] D. Garcia-Gamez, P. Green and A. M. Szelc, *Predicting transport effects of scintillation light signals in large-scale liquid argon detectors*, *The European Physical Journal C* **81** (2021) 349.

[4] B. Abi, A. A. Abud, R. Acciarri, M. Acero, G. Adamov, M. Adamowski et al., *First results on protodune-sp liquid argon time projection chamber performance from a beam test at the cern neutrino platform*, *Journal of instrumentation* **15** (2020) P12004.

[5] A. Machado, E. Segreto, D. Warner, A. Fauth, B. Gelli, R. Maximo et al., *The x-arapuca: an improvement of the arapuca device*, *Journal of instrumentation* **13** (2018) C04026.

[6] A. Falcone, A. Andreani, S. Bertolucci, C. Brizzolari, N. Buckanam, M. Capasso et al., *Cryogenic sipm arrays for the dune photon detection system*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **985** (2021) 164648.

[7] DUNE collaboration, A. Minotti, *Characterization of the dune photodetectors and study of the event burst phenomenon*, in *Journal of Physics: Conference Series*, vol. 2156, p. 012242, IOP Publishing, 2021.

[8] M. Guarise, M. Andreotti, R. Calabrese, A. C. Ramusino, V. Cicero, M. Fiorini et al., *A newly observed phenomenon in the characterisation of sipm at cryogenic temperature*, *Journal of Instrumentation* **16** (2021) T10006.

[9] A. A. Abud, B. Abi, R. Acciarri, M. Acero, M. R. Adames, G. Adamov et al., *Scintillation light detection in the 6-m drift-length protodune dual phase liquid argon tpc*, *The European Physical Journal C* **82** (2022) 618.

[10] N. Gallice, D. collaboration et al., *Xenon doping of liquid argon in protodune single phase*, *Journal of Instrumentation* **17** (2022) C01034.

[11] D. Caratelli, W. Foreman, A. Friedland, S. Gardiner, I. Gil-Botella, G. Karagiorgi et al., *Low-energy physics in neutrino lartpcs*, *arXiv preprint arXiv:2203.00740* (2022) .

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