The Photon Detection System of the DUNE Far Detector

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Summary. — The Deep Underground Neutrino Experiment (DUNE) will deploy innovative photon detectors, known as X-Arapucas, within its Far Detector to achieve a trigger for non-beam events and complementary calorimetry. This work describes the design of the DUNE far detector and the Photon Detection System for both Horizontal Drift and Vertical Drift modules and introduces the ProtoDUNE prototypes at CERN.

1. – Introduction

Since their discovery, neutrinos have captivated physicists worldwide, leading to many theories and experiments to unveil their mysterious nature. Despite extensive efforts, numerous open questions remain, and addressing one or more of these questions could profoundly impact our understanding of particle physics and the universe. Consequently, there is a strong motivation to develop new instruments, such as the Deep Underground Neutrino Experiment (DUNE) [1], which will employ innovative technologies and the most powerful available neutrino beam to study CP violation in the neutrino sector and determine the neutrino mass ordering. Beyond these goals, the detector configuration will enable additional physics studies, such as supernova and solar neutrinos detection and search for physics beyond the Standard Model.

DUNE will consist of a Near Detector complex, located close to the neutrino beam at Fermilab (Illinois), and a Far Detector (FD) at SURF (South Dakota), 1300 km away. The FD will comprise four detectors, with two of them operating during Phase I of the experiment: a vertical drift (VD) and a horizontal drift (HD) 17-kton LAr TPC. The remaining two, planned for Phase II, are currently under design. Both VD and HD will exploit the possibility of detecting scintillation light in argon using a Photon Detection System (PDS) composed of innovative detectors called X-Arapuca. The X-Arapucas will trigger non-beam events, enabling the experiment to achieve many of its primary scientific goals. Additionally, they will contribute to the neutrino interaction vertex and primary

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track reconstruction while providing a complementary calorimetric measurement. Two 750-ton LAr prototypes were built at CERN to test this technology and are currently in operation. In this work, the DUNE PDS will be described, along with a report on the ongoing activities involving the CERN prototypes.

2. – The DUNE experiment

The Deep Underground Neutrino Experiment (DUNE) is a new-generation long-baseline neutrino experiment with the main scientific goals of studying the neutrino mass ordering and the leptonic CP-violating phase, along with the detection of astrophysical neutrinos and the search for physics beyond the Standard Model. DUNE will employ a high-power proton beam of 1.2 MW (upgradable to 2.4 MW) to produce neutrinos in the GeV energy range and will feature two experimental sites. The first site, denoted as Near Detector (ND) [2], will be located at Fermilab, at 575 m distance from the neutrino beam source. The second one, the Far Detector (FD) [3], will be placed at the SURF laboratory, 1300 km from Fermilab and 1500 m underground. A schematic view of the DUNE experiment is shown in Fig.1.

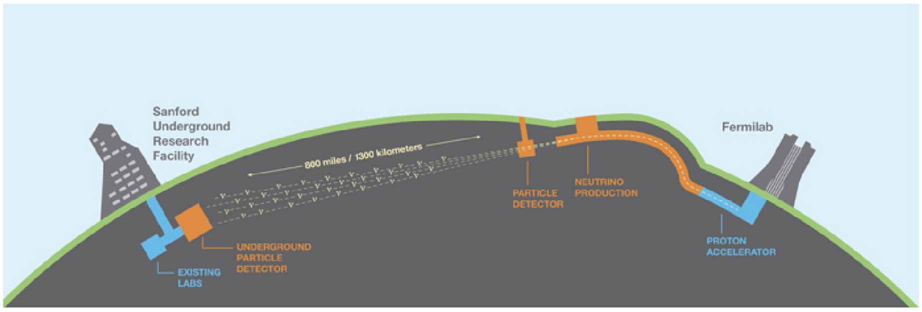

Fig. 1. – Representation of the DUNE experiment with the two laboratories. At Fermilab, in Chicago, the neutrino beam will be produced and the near detector will operate. The far detector will be installed at the SURF laboratory, in Sanford, located at 1300 km distance from the neutrino production point [3].

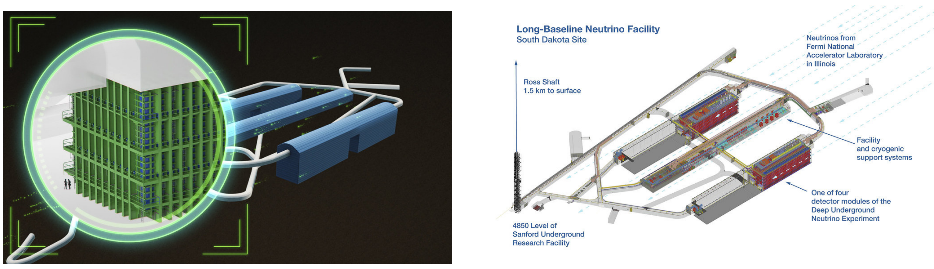

Fig. 2. – Representation of the DUNE far detector site with caverns and detectors [3].

The FD (Fig.2) will consist of four modules. Two of them (FD1 and FD2) are scheduled for installation during Phase 1 of the experiment. They will be single-phase Liquid Argon Time Projection Chamber (LArTPC) modules, each with a mass of 17.5 kton, with horizontal drift for FD1 and vertical drift for FD2. The remaining two modules, to be deployed during Phase 2, are still under design development. The FD configuration is intended to enable high-resolution imaging of neutrino interactions and provide fast timing for triggering, thus supporting precise measurement of neutrino oscillation parameters and the detection of neutrinos from natural sources.

The ND complex will comprise three large detectors: two of them capable of moving off the beam axis to sample different neutrino energies, and one fixed on the beam axis to serve as a beam monitor. These detectors will constrain systematic uncertainties in the oscillation analysis, measure neutrino cross sections, and perform beyond-standard-model searches.

3. – DUNE Far Detector modules

The DUNE far detector modules will employ a double readout technique. Specifically, they will instrument a TPC to detect the particle's charge and a Photon Detection System (PDS) for scintillation light detection. Having a double readout has the advantage of a better neutrino interaction vertex reconstruction, combined calorimetry and having a prompt signal for non-beam events (given by the scintillation light).
The first two modules are called Horizontal Drift (HD) and Vertical Drift (VD), referring to the drift direction of the charged particles. The Horizontal drift (Fig.3, left) will be composed of four 3.6 m × 12 m × 58 m drift regions, 3 anodes and 2 cathodes. The TPC will be formed by Anode Plane Assemblies (APAs), based on wire chamber technology, and the PDS will be installed in the APAs. The Vertical Drift (Fig.3, right) will be the first module to be delivered. It will be composed of two 13.5 m × 60 m × 6.5 m drift volumes, 2 anodes and 1 cathode. In this case, the TPC will be based on Charge Readout Planes (CRPs), based on perforated PCB technology, and the PDS will be installed in the cathode and on the walls.

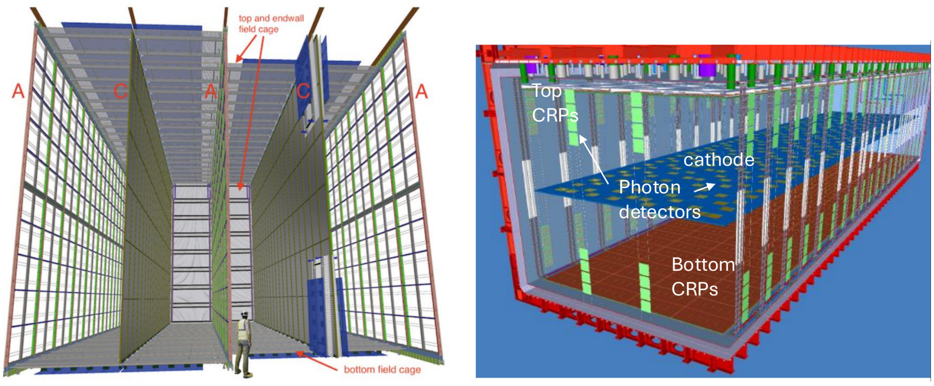

Fig. 3. – The DUNE far detector modules. The Horizontal Drift module is shown on the left, the Vertical Drift on the right.

4. – The Far Detector Photon Detection System

The Photon Detection System (PDS) is based on the innovative X-Arapuca detectors [5]. These are composed of several layers, acting like a trap for photons (Fig.4, left). The incoming photons will encounter first the P-terphenyl layer (PTP), which converts the LAr scintillation light from a 128 nm to 350 nm wavelength. Next, there is a dichroic filter, with the property of being transparent to wavelengths smaller than 400 nm and reflective to wavelengths larger than 400 nm, allowing the PTP converted light to enter. After the filter, a wavelength shifter bar is placed to convert the incoming light to 430 nm. The converted light can not go back and cross the dichroic filter, with the result of having a light-trap. Finally, the X-Arapuca is instrumented with SiPMs to detect the trapped photons.

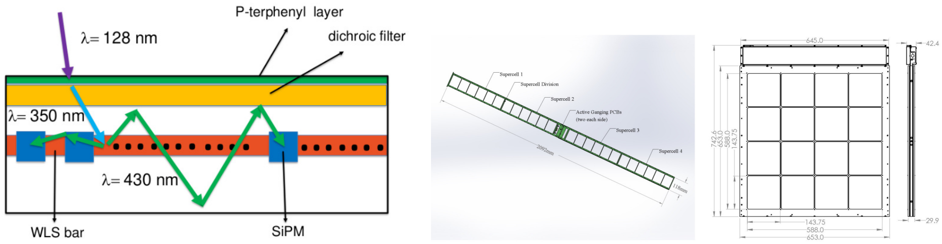

Fig. 4. – X-Arapuca photon detectors. On the left, the X-Arapuca concept of trapping photons by using layers of various materials is presented. On the right, the supercell and megacell X-Arapucas are shown. These two design will be employed in the horizontal and vertical drift detectors respectively.

4·1. *HD and VD Photon Detection System.* – Two different PDS design have been proposed and tested for the HD and VD, called supercells and megacells respectively.
For the HD, the photon detector (PD) modules will be made of 4 X-Arapuca supercells, of 49 cm × 10 cm, read by 48 SiPMs per supercell. Every APA will instrument 4 PD modules, for a total of 1500 PD modules and no influence on the active volume. The VD detector will feature megacell X-Arapucas, of 65 cm × 65 cm, read by 160 SiPMs. There will be 320 double-face X-Arapucas installed on the Cathode and 352 single-face X-Arapucas installed on the walls. The two X-Arapuca design are shown in Fig.4, on the right. The Cathode X-Arapucas will employ the innovative Power Over Fiber (PoF) and Signal Over Fiber (SoF) technology [6]. The PoF and SoF are essential to power the electronic systems operating in high voltage environment and receive the signal recorded by the SiPMs.

5. – ProtoDUNE at CERN

A testing facility, called neutrino platform, has been built at the CERN Prévessin site for building and testing the DUNE prototypes (Fig.5). The prototypes (protoDUNEs) have 8 m^3 dimensions and are filled with 760 tons of LAr. The protoDUNEs instrument a TPC, a PDS and a Cosmic-Ray Tagger for tests with cosmic rays.
The protoDUNE-HD is the first prototype built (Fig.6, left). It is composed by 4 APAs (2 per side) and a cathode in the middle. It has a 0.28 kton fiducial volume, a 500 V/cm electric field and a drift length of 3.6 m. The 4 APAs are composed of 3 layers of wire planes, and the PDS is integrated in the APAs. There are 40 X-Arapuca modules in total (10 per APA), with absolute efficiency of 2-3%, and 48 SiPMs per X-Arapuca. The protoDUNE-HD was successfully operated from May 2024 to December 2024, and the data analysis is ongoing.

The second prototype is the protoDUNE-VD (Fig.6, right), with 4 horizontal CRPs (2 at the top and 2 at the bottom), a cathode in the middle, and a 3.5 m drift region. The VD has 16 megacells X-Arapuca modules, 8 on the cathode and 8 on the walls (behind the field cage), read by 160 SiPMs each. The protoDUNE-VD is smoothly taking data at CERN from spring 2025 and it will continue its operation until the end of 2025.

Fig. 5. – Neutrino Platform at the CERN Prévessin site. The two protoDUNE detectors are inside the two red cryostats.

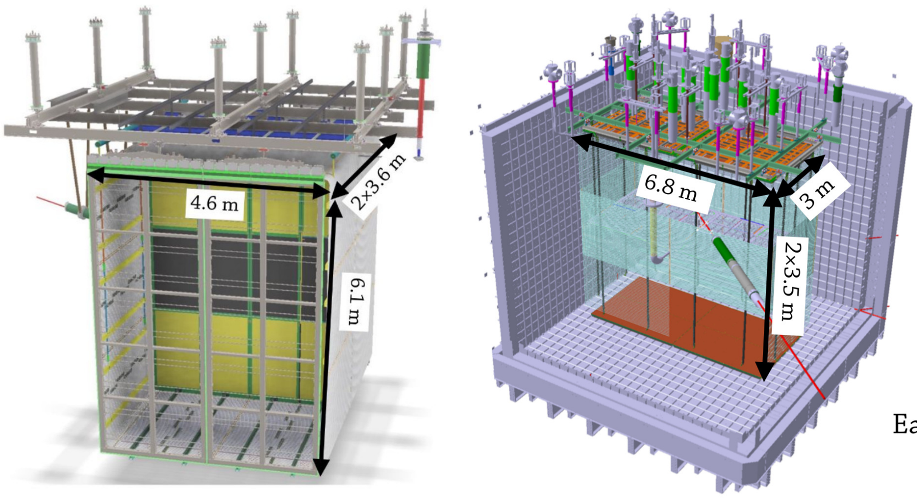

Fig. 6. – ProtoDUNE-HD on the left and protoDUNE-VD on the right.

6. – Summary and conclusions

The Deep Underground Neutrino Experiment (DUNE) is a future long-baseline neutrino oscillation experiment. It will be built on two experimental sites, one at Fermilab called the near detector and the other at SURF called the far detector. The far detector will be composed of four 17-kton LAr modules, employing a double readout for charge and light. The first two modules are called horizontal and vertical drift (referring to the charge drift), and they are already designed. An innovative photon detection system based on X-Arapuca detectors will be used in the HD and VD modules, with two different designs. The prototype of the HD detector was successfully tested at the CERN neutrino platform. The VD prototype is currently under test in the same facility and new results will come in the upcoming months.

REFERENCES

[1] Babak Abi et al. Long-baseline neutrino oscillation physics potential of the DUNE experiment. The European Physical Journal C, 80(10):1–34, 2020.
[2] A. Abed Abud et al. Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report, 2021.
[3] ABI, Babak, et al. Deep Underground Neutrino Experiment (DUNE), far detector technical design report, volume II: DUNE physics. arXiv preprint arXiv:2002.03005, 2020.
[4] M. Andreotti et al. Coded masks for imaging of neutrino events. The European Physical Journal C, 81(11), November 2021.
[5] A. Machado, E. Segreto, D. Warner, A. Fauth, B. Gelli, R. Máximo et al., The x-arapuca: an improvement of the arapuca device, Journal of Instrumentation 13 (2018) C04026–C04026.
[6] M.A. Arroyave et al., Characterization and novel application of power over fiber for electronics in a harsh environment (2024) JINST 19 P10019.