ProtoDUNE-HD Photon Detection System performances: SiPM breakdown voltage

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Summary. — The ProtoDUNE-HD detector is a prototype for the second Far Detector (FD) module of the Deep Underground Neutrino Experiment (DUNE), a next-generation long-baseline experiment for neutrino physics. It consists in a horizontal drift liquid argon time projection chamber, that was constructed and operated at the CERN Neutrino Platform during 2024. In particular, the FD Photon Detection System (PDS) is critical for the DUNE physics program. Indeed, the reference time of the event, needed to reconstruct the neutrino interaction, is given by the scintillation light detected by X-ARAPUCA modules, *i.e.*, photon traps instrumented with Silicon PhotoMultipliers (SiPMs). In this paper, the ProtoDUNE-HD PDS design and first preliminary results about its operation are described, focusing on SiPM breakdown voltage studies. Thanks to this work, an optimization of the FD can be performed, in order to achieve DUNE scientific goals.

1. – Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, international, long-baseline experiment for neutrino physics, currently under construction in the US [1]. DUNE will consist of two detectors exposed to an intense neutrino beam. The Far Detector (FD) will include four Liquid Argon Time Projection Chamber (LArTPC) modules, which allow the detection of the products of neutrino-argon interactions by measuring charge and scintillation signals [2].

The ProtoDUNE-HD detector is a prototype for the second DUNE-FD module, implemented with Horizontal Drift (HD) technology for the charge collection. It was constructed and operated in the NP04 cryostat at the CERN Neutrino Platform during 2024. Its successful operation will demonstrate the effectiveness of the FD-HD design.

In this paper, a brief overview of the second DUNE FD module design and ProtoDUNE-HD Photon Detection System (PDS) is presented, along with first results about ProtoDUNE-HD operation performances, focusing on breakdown voltage studies.

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2. – The DUNE experiment

DUNE will consist of two detectors exposed to an intense neutrino beam, produced at Fermi National Accelerator Laboratory (FNAL), in Illinois, as shown in fig. 1. The neutrino beam is designed to be the most intense in the world and will be provided by the Long Baseline Neutrino Facility (LBNF) at FNAL. LBNF is based on the Proton Improvement Plan II (PIP-II), delivering an up to 1.2 MW proton beam from FNAL's Main Injector (later upgradeable to 2.4 MW), with energy ranging between 60 and 120 GeV. From the decay of secondary mesons (primarily pions and kaons), produced when high-energy protons strike a graphite target, a beam of muonic neutrinos or antineutrinos is created, with energies ranging from 0.5 to 8 GeV and a small electron neutrinos contamination of approximately 1%.

The Near Detector (ND) is located 574 m from the neutrino production point, to characterize the initial neutrino beam, the detector response and the cross-sections of neutrino interactions, and will feature three detectors: ND-LAr, a modular LArTPC with approximately 50 t fiducial mass, TMS, a magnetized steel-scintillator spectrometer, and SAND, a magnetized beam monitor.

The Far Detector is located 1300 km from the ND and about 1.5 km underground, at Sanford Underground Research Facility (SURF), in South Dakota, and will consist of four LArTPC modules with a fiducial mass of at least 10 kt and a volume of approximately $[14 \times 15 \times 62]\,\mathrm{m}^3$ each [3]. DUNE is planning for and currently developing two single-phase LArTPC technologies for the first two FD modules, where all the detector elements inside the cryostat are immersed in Liquid Argon (LAr) at 88 K: a horizontal drift and a vertical drift detector, in which the electric field is oriented in the horizontal or in the vertical axis, respectively.

The ND and FD combined data will allow the measurement of the neutrino oscillation probabilities as a function of the neutrino energy to obtain the neutrino oscillation parameters, with particular attention for the Charge conjugation Parity (CP) violating phase (δ_{CP}), the mass hierarchy and the octant of the mixing angle θ_{23}. Furthermore, DUNE will search for low energy non-beam events, namely supernova neutrino bursts and Beyond Standard Model events, *e.g.*, the proton decay.

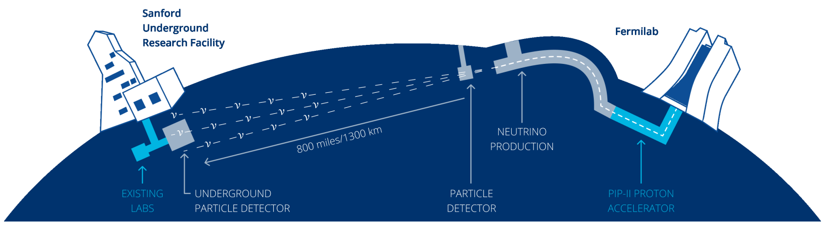

Fig. 1. – Schematic of the global view of DUNE.

3. – DUNE FD-HD Photon Detection System

The LArTPC detector technology enables 3D particle imaging with millimetric resolution. The topology of a neutrino interaction is reconstructed from the tracks of secondary charged particles, which produce both free charge carriers by ionization and scintillation light. Ionization electrons move horizontally towards the anodic wires planes, composed by Anodic Plane Assemblies (APAs), thanks to an intense electric field of 500 V/cm, and allowing the reconstruction of two spatial coordinates and calorimetric measurements. The argon scintillation light, at 127 nm, is detected by the PDS and provides the timing of the event for the reconstruction of the third spatial coordinate, as well as the trigger for low energy non-beam events and a separate energy measurement.

The DUNE FD will implement a modular PDS, composed by several unit cells called X-ARAPUCAs, which act as light traps instrumented with Silicon PhotoMultipliers (SiPMs) [5]. The X-ARAPUCAs of the FD-HD module are called SuperCells, and are placed behind each APA. They consist of a dichroic filter, with a sharp cut-off at 400 nm, coated with a p-Terphenyl (PTP) layer that shifts the 127 nm photons to approximately 350 nm. The inner walls are covered by highly reflective (> 90%) foils, while a light guide also acting as wavelength-shifter (WLS) converts photons to 430 nm and guides them to the SiPMs. Fig. 2 shows the structure and the working principle of a SuperCell.

Each SuperCell is implemented by 48 SiPMs, which are arranged in 8 mounting boards of 6 SiPMs each. Two different SiPM models from two vendors are used: HPK-S16517 from Hamamatsu Photonics (HPK) and FBK-NUV-HD-CryoTT from Fondazione Bruno Kessler (FBK). The SuperCell signal is read-out by a dedicated electronics called DAPHNE (Detector electronics for Acquiring PHotons from NEutrinos), which is responsible also for the SiPM biasing. Each DAPHNE board has 40 read-out channels arranged in five different groups, corresponding to five Analog Front-Ends (AFEs), each of which provides the same bias voltage to its eight channels. One DAPHNE channel corresponds to a SuperCell module. The bias voltage is controlled through two parameters: V_{bias}, which provides coarse tuning in steps of approximately 0.7 V, and V_{trim}, which allows a negative fine adjustment with a resolution of about 1 mV.

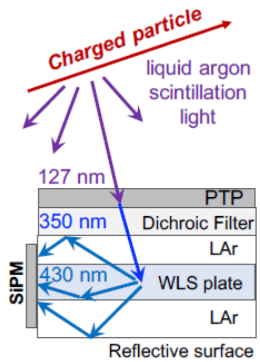

Fig. 2. – Schematic of X-ARAPUCA SuperCell structure (not in scale).

4. – ProtoDUNE-HD PDS

ProtoDUNE-HD was designed to test and validate the technologies for the second DUNE FD module. It has been operated in the NP04 cryostat at the CERN Neutrino Platform, between February and November 2024. It was exposed to a charged particle beam for 10 weeks from the H4 beam line: protons from the Super Proton Synchrotron (SPS) strike the T2 target about 600 m upstream of the detector, generating secondary particles that collide with secondary targets producing particles with momenta between

0.5 GeV/c and 7 GeV/c [4]. ProtoDUNE-HD has collected around 30 million beam and cosmic interactions.

ProtoDUNE-HD aims to test the FD components at real scale. The active volume is $[4.6 \times 6.1 \times 7.2]\,\mathrm{m}^3$, with four APAs placed on both sides of a central cathode, resulting in two drift volumes of 3.6 m each. 40 X-ARAPUCAs are placed behind each APA. Four different X-ARAPUCA configurations were used, by combining two different WLS manufacturers (Eljen and G2P) and two SiPM models (HPK and FBK). Seven DAPHNE boards have been used for the ProtoDUNE-HD operation, each identified by an IP address.

To monitor the ProtoDUNE-HD PDS performances, the main parameters, *e.g.*, SiPM breakdown voltage (V_{bd}), were periodically measured in appropriated calibration runs and compared with results previously obtained in laboratory, while determination of other parameters is being done in appropriate offline analysis using beam and cosmic data.

4˙1. *Breakdown voltage monitoring.* – The breakdown voltage is a fundamental parameter of a SiPM, since its Photon Detection Efficiency (PDE) depends on the bias voltage applied, which is usually expressed as $V_{bd} + OV$, being OV the overvoltage [6]. This parameter can be computed from the current-voltage (IV) curve, by identifying the sudden change in the slope of the current. This point can be obtained by searching for the maximum of the first derivative of the IV curve.

DAPHNE boards allow to perform IV scans to measure the V_{bd} of a SuperCell. Firstly, a bias scan with V_{trim} at zero up to a fixed limit is performed, and the last point is taken as V_{bd} bias component. Then, a trim scan with V_{bias} fixed at the previous value is performed and a parabolic fit of the first normalized derivative is done, to search for the maximum and obtain V_{bd} trim component. The two results are then combined to have the V_{bd} estimation. Fig. 3 shows a typical trim IV curve analysis.

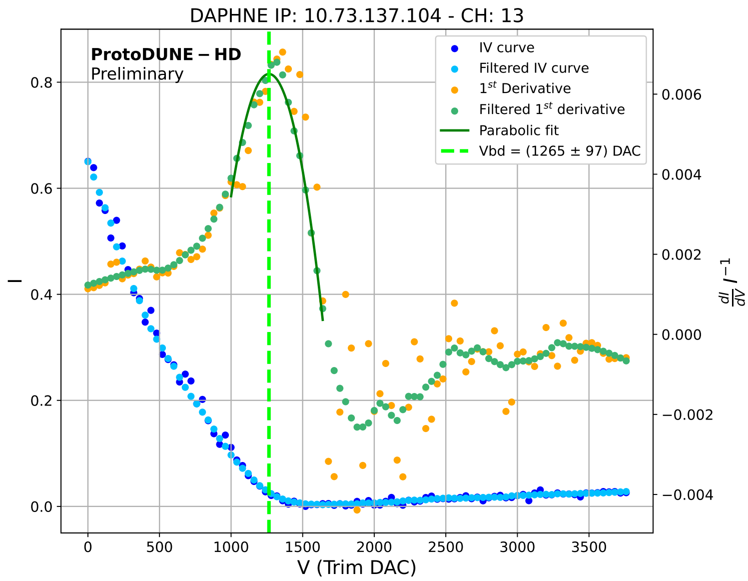

Fig. 3. – Example of a trim IV curve analysis to determine V_{bd} for a DAPHNE channel mounting HPK sensors.

To study the time stability of V_{bd} through ProtoDUNE-HD operation, dedicated IV runs were acquired nearly twice a month. Fig. 4 shows an example of the V_{bd} evolution of each channel for an AFE, normalized to the average V_{bd} of all FBK or HPK sensors, over a period of four months, and being the error bars the standard deviation. Variations are below 2%, and this is true for all SuperCells. The mean V_{bd} value for FBK sensors is (27.5 ± 0.2) V, while for HPK is (42.0 ± 0.5) V, where error is the standard deviation.

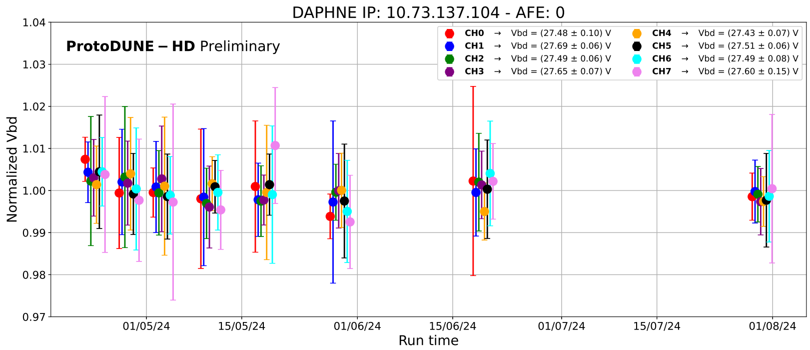

Fig. 4. – Example of normalized V_{bd} evolution in time for a DAPHNE AFE.

The ProtoDUNE-HD V_{bd} results are compared with previous measurements taken in Liquid Nitrogen (LN). Indeed, the 60% of SiPMs mounted in ProtoDUNE-HD PDS were characterized by CACTUS (Cryogenic Apparatus for Continuous Tests Upon SiPMs), a custom setup developed at Ferrara and Bologna Universities-INFN sites to automatically characterize a large number of sensors in parallel, by acquiring also IV curve for the V_{bd} determination at LN temperature. In addition, after the SuperCell assembly, modules built in Università degli Studi Milano Bicocca (MIB) and CIEMAT were tested in LN, and from gain study at different OV the V_{bd} was evaluated as voltage at which gain reaches zero. Fig. 5 shows the comparison between the three different measurements. Two different populations are clearly visible for HPK and FBK sensors. Moreover, there is a discrepancy between V_{bd} measured in ProtoDUNE-HD and measurements taken previously in laboratories. This is due to the fact that V_{bd} decreases with temperature decreasing and CACTUS and SuperCell studies were carried out in LN at 77 K, while others in LAr at 88 K. The mean discrepancy between ProtoDUNE-HD and CACTUS measurements for FBK modules is (0.7 ± 0.2) V, while for HPK is (0.5 ± 0.3) V, where error is the standard deviation.

5. – Conclusions

The Photon Detection System is a critical component of the DUNE experiment's far detector. To validate the technology for the second FD module, it is extremely important to monitor and estimate the performances of the PDS during ProtoDUNE-HD operation. Performance studies show excellent stability of the breakdown voltage during the whole operation period, with a good agreement with laboratory measurements, ensuring that PDE changes were small and within requirements, and that there have been no clear signs of deterioration in the sensors.

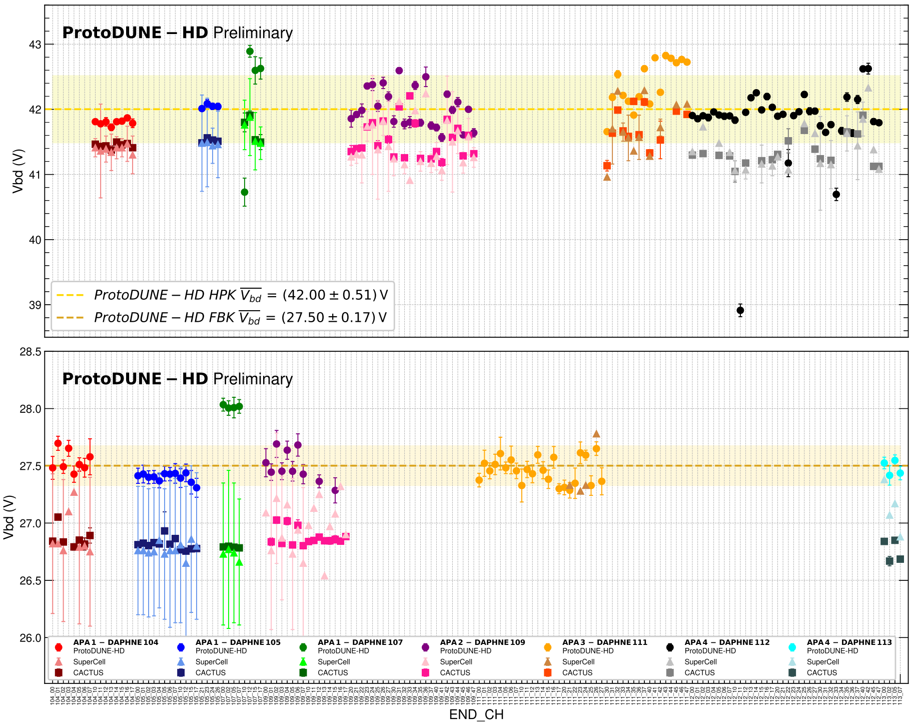

Fig. 5. – V_{bd} comparison between ProtoDUNE-HD (circle), SuperCell (triangle) and CACTUS (square) measurements, with HPK sensors at the top and FBK at the bottom. Each ProtoDUNE-HD channel is identified with two numbers: END, related to the IP of the DAPHNE board, and CH, related to the DAQ channel number.

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