PROCEEDINGS OF SCIENCE

The DUNE Photon Detection System

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DUNE is an underground neutrino oscillation experiment that will be performing precision measurements of the PMNS matrix to determine unambiguously the mass ordering and the leptonic CP violation. It also comprises a rich non-accelerator physics program for the detection of supernova neutrinos, nucleon decay, and BSM physics. DUNE employs a high-power neutrino beam under construction at Fermilab together with the DUNE Near Detector, and four liquid argon TPCs (Far Detector) that will be installed at the Sanford Underground Research Facility in South Dakota, 1300 km away from the neutrino source. The photon detection system (PDS) – which records the 128 nm scintillation light of argon and provides the time of interaction of the beam neutrinos in the Far Detector - is critical for studying nucleon decay and detecting Supernova Neutrino Bursts. The PDS also complements the calorimetric measurement performed by the TPC (i.e. the charge readout) and contributes to the energy calibration and time performance of the Far Detector. The article is an overview of the design of the PDS for the first DUNE far detector module, with special emphasis on VUV light trapping in a cryogenic environment, its technical challenges, and the expected physics performance. The status of the construction of the PDS and its validation in the Run II of ProtoDUNE-SP will be also presented.

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[*] Speaker

1. Introduction

Ultra-violet photon detection in liquefied noble gases plays a prominent role in several neutrino and dark matter experiments, whose needs have fostered the development of cryogenic silicon photomultipliers (SiPMs). Among the experiments that employ a photon detection system (PDS) for the scintillation light of liquid argon, DUNE [1] poses major challenges in terms of scalability to large volumes (17 kton per module) and long-term reliability. In particular, the first DUNE module is based on a compact anode plane assembly (APA) [2] where the PDS must be located. Space constraints thus highly favor the use of SiPM arrays, which must be coupled to a system for light trapping and transport. The first DUNE module will use the X-Arapuca as light trapping system. In the first section we describe the X-Arapuca detector and the tests performed on it, while in the second section we describe the SiPM models and the selection procedure. In the last paragraph, the cold and warm electronics will be described.

2. Light collectors: X-Arapuca

The ARAPUCA [3] is a light trap that captures wavelength-shifted photons inside a box with highly reflective internal surfaces until they are eventually detected by SiPMs (see Fig. 1).

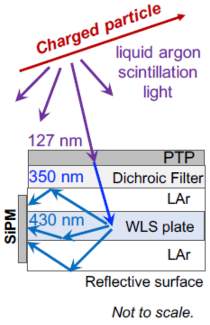

Figure 1: Working principle of an X-ARAPUCA cell.

An X-ARAPUCA [4] cell is based on a 10.0×7.8 cm^2 dychroic filter coated with p-Terphenyl (PTP). The argon scintillation photons at 128 nm impinging on the PTP layer are shifted to 350 nm. The photons emitted toward the cell enter the filter, which has a cutoff wavelength of about 400 nm. A wavelength shifting (WLS) bar with an emission wavelength larger then the transmission range of the filter is installed inside the cell, while the inner lower surface is covered with a reflective layer. Wavelength shifted photons from this plate are either transported along the WLS plate to the photosensors via total internal reflection, or if they escape the plate, may be captured within the dichroic filter. Arrays of SiPMs are positioned along the lateral walls of the cell to detect the photons. The cells are be assembled in series of 6 to form a supercell (488 × 100 × 8 mm^3), read by the same acquisition channel. Four supercells will compose a bar (2092 × 118 × 23 mm^3), that will be installed between the APA planes. To test the light collection uniformity and efficiency a 2-window supercell has been tested in Milano Bicocca [5]. In the same configuration two different

WLS plates have been employed: a commercial (Eljen 286) WLS plate, with a measured PDE of 2.8%, and a new WLS bars (FB118-2, Acrylic matrix, higher efficiency) developed at MiB with PDE measured in same test stand 3.8% (see Fig. 2) [5].

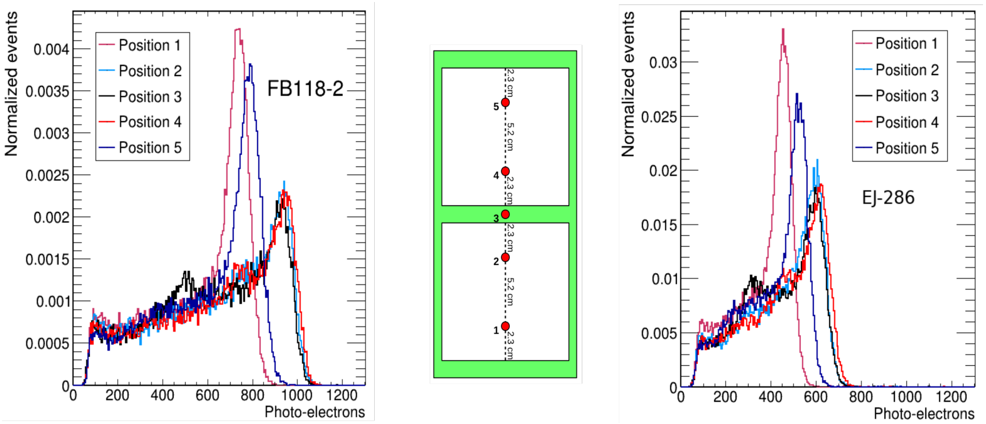

Figure 2: The α spectrum in number of detected photoelectrons for five source positions: the X-Arapuca is equipped with FB118 (left) and EJ-286 (right) respectively [5].

Several DUNE labs have been developing facilities for the tests of the supercells. At the time of writing, they are performed in Univ. of Milano-Bicocca, Milano and CIEMAT (Madrid), Coating and assembly infrastructures are being completed in University of Campinas and Colorado State University.

3. Photosensors

Silicon Photomultipliers (SiPM) are a type of photosensors largely employed in DUNE. Two photosensor vendors are being investigated, Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK). They provided 6 types (splits) of 6x6 mm^2 SiPMs developed specifically for DUNE: HPK S13360 LQR/HQR 50/75 μm pitch (4 splits) and FBK NUV HD LF Single/Triple Trench (2 splits). In 2021, we carried out a test program that confirmed that all splits fulfil the DUNE specifications:

- dark count rate (DCR) lower than 100 mHz/mm^2;
- correlated noise lower than 35%;
- signal-over-noise (S/N) higher than 4;
- no damage or malfunctioning after 20 thermal cycles in liquid nitrogen.

The first delivery of customized SiPMs for DUNE consisted of 25 SiPMs of each type (6 batches). They were fully characterized trough:

- IV curve measurements at room and at 77 K temperature;

PDE	Gain (10^6)	DCR (mHz/mm^2)	Crosstalks (%)	Afterpulses (%)
40	3.73	57.54	6.62	0.86
45	4.59	64.97	8.97	1.10
50	5.44	66.32	10.96	1.30

Table 1: Preliminary results of measurements for the HPK HQR 75 μm photosensors [7].

- gain, S/N and DCR measured in nitrogen bath at the overvoltage to obtain 40%, 45%, and 50% of PDE;
- 20 thermal cycles with controlled cooling down and warming up;
- all measurements were repeated after the thermal stress.

As mentioned above, all splits fulfilled the DUNE specifications. For the final selection procedure, the vendors provided 250 SiPMs per split to test compliance with the specifications in a larger sample. We employed here a faster procedure; it mimics the quality tests that will be carried on during mass production and comprises IV measurements for all SiPMs at room and 77 K temperature and 20 thermal cycles with controlled cool down and warm up. The IV measurements were repeated for all SiPMs. We performed then a complete characterization of a photosensor subsample (5% of the SiPMs per split).

We also performed tests with 48 SiPM in active ganging at different overvoltages (OV) per each split, with measurements of S/N and signal shape (see Sec. 4). After those tests, the HPK HQR 75 μm and FBK Triple Trench splits were selected thanks to their superior performance in active ganging mode. The main results of the measurements for the HPK downselected split are summarized in Tab. 1.

The ProtoDUNE run II production consists of 4000 FBK SiPMs and 4000 Hamamatsu SiPMs. Dedicated test stand for automatic IV curve and DCR measurements are being completed in Bologna, Ferrara, and Valencia in the framework of the Photon Detection System (PDS) DUNE Consortium.

4. Cold and warm eletronics

A dedicated cold electronics board was developed in Milano Bicocca, to collect the signals of 48 SiPMs of a supercell into a single readout channel [6]. Each channel reads out 48 6x6 mm^2 SiPMs, with 60 nF total input capacitance. It is based on a two-stage amplifier, composed by a SiGe bipolar transistor and a fully differential op-amp. The SiGe input transistor gives 0.37 nV/$\sqrt{\text{Hz}}$ at cryo temperature and provides low power consumption (2 mW/channel) to prevent boiling of liquid argon. The board was tested with all candidate SiPMs for DUNE. It provides a fast response, with lower than 100 ns rise time, dynamic range greater than 2000 p.e. and a S/N of 5-10 depending on SiPM type and overvoltage (at 45% PDE, S/N=5.96 for the HPK HQR 75 μm and 7.16 for the FBK Triple Trench), allowing a clear separation of photoelectron peaks when the 48 SiPMs are read out in parallel (see Fig. 3).

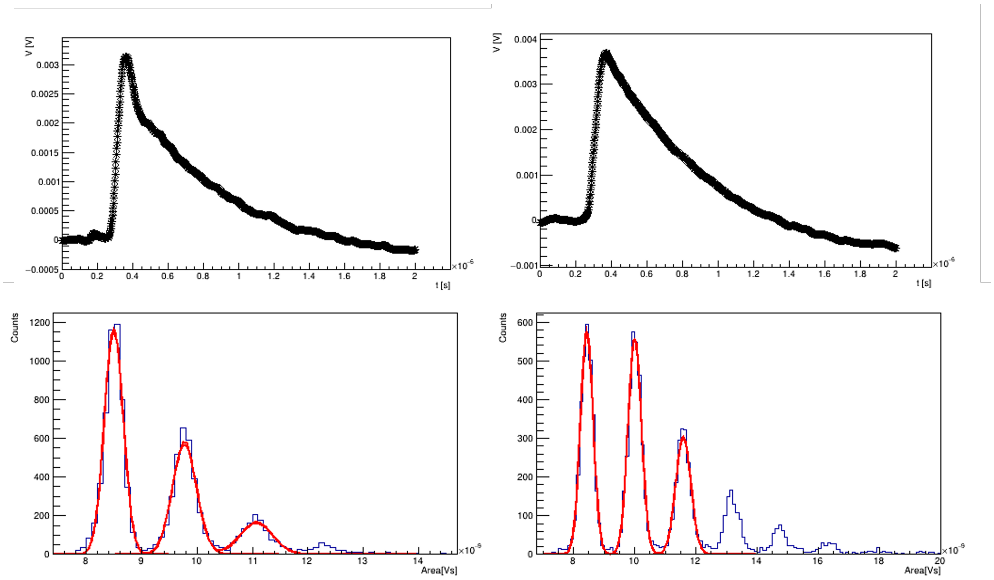

Figure 3: (Top) Mean 1 p.e. waveform and (bottom) and signal histogram for HP HQR 75 *mu*m (left) and FBK Triple Trench (right) respectively.

The design of the DAPHNE (Detector electronics for Acquiring PHotons from NEutrinos) warm electronic board is inherited from the readout board of the Mu2e experiment. It is based on a Artix-7 FPGA, with a 14 bit ultrasound ADC and a Bias-Trim Voltage supply. It provides a gigabit link up to 6.6 Gb/s to FELIXDAQ/full-mode protocol for the DUNE Timing interface [2].

References

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