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Performance of the DUNE Photon Detection System(*)

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Summary. — DUNE (Deep Underground Neutrino Experiment) is a long-baseline experiment currently under construction at the Sanford Underground Research Facility (SURF) in South Dakota, US. The Far Detector (FD) is based on the Liquid Argon Time Projection Chamber (LAr-TPC) technology. The main physics goals of DUNE include determining the mass ordering of neutrinos with a significance greater than $> 5\,\sigma$ and measuring the CP-violating phase in the lepton sector by studying neutrino oscillations. DUNE is also expected to be highly competitive in studying astro-particle phenomena, such as solar, atmospheric, and supernova neutrinos. The Photon Detection System (PDS) serves as the trigger for non-beam events in the experiment and provides the estimation of the absolute time of an event. This capability enables the reconstruction of the interaction vertex with a precision on the order of 1 mm. Additionally, the PDS enhances the energy resolution of the experiment with the combined *charge-light calorimetry*.

1. – Overview

To perform the combined charge-light readout calorimetry and to expand the experiment's physics program, DUNE requires a highly performing Photon Detection System [1]. The PDS must ensure a large active surface and high efficiency to achieve an average light yield greater than 20 photoelectrons per MeV of deposited energy throughout the active volume.

The first two modules of the Far Detector (FD), two 10 kton LAr-TPCs, will have similar light readout technologies. The PDS comprises a light trap, called X-ARAPUCA [2], capable of converting the ultraviolet photons (127 nm), emitted from the liquid argon scintillation, to visible light (~ 430 nm) and directing it to arrays of silicon photomultipliers (SiPMs). The signals from these cryogenic SiPMs are connected in parallel and amplified by a trans-impedance amplifier operated in liquid argon. The signal digitisation, however, is performed at room temperature by the DAPHNE board.

(*) IFAE 2023 - "Poster" session

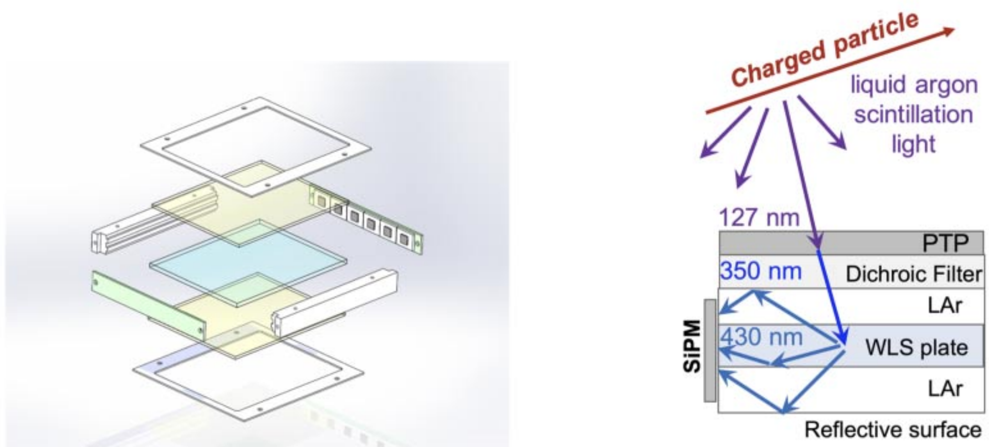

Fig. 1. – Exploded view (left) and schematic working principle (right) of an X-ARAPUCA.

2. – X-ARAPUCA

The core of the Photon Detection System technology is the X-ARAPUCA [3,4]. This device utilises two wavelength shifters (WLS) and a dichroic filter between them to trap light in a small volume surrounded by SiPMs until photons are detected. The external WLS consists of a para-Terphenyl (PTP) layer that converts 127 nm to 350 nm photons, falling below the 400 nm cutoff of the dichroic filter. The innermost component of the X-ARAPUCA is a WLS plate that shifts the photon wavelength to 430 nm, matching the range of maximal efficiency for the SiPMs. This design maximises the active surface of the PDS, enabling the collection of more light while maintaining a cost-effective system and meeting the space constraints of the TPC.

The X-ARAPUCA geometry differs between the DUNE FD-1 and FD-2 modules: the former has a rectangular surface of 60 cm×10 cm with 48 SiPMs, while the latter is square-shaped with sides of 60 cm and 160 SiPMs forming two independent electronic channels.

Both design have demonstrated a photon detection efficiency of $\sim$ 2-3%, fulfilling the light yield requirement.

3. – SiPMs

The DUNE SiPMs are custom products developed by two different vendors: Hamamatsu Photonics K.K. (HPK) in Japan and Fondazione Bruno Kessler (FBK) in Italy. The experimental requirements for these photosensors include intrinsic photon detection efficiency, signal-to-noise ratio (SNR), long-term reliability in a cryogenic environment, and dark count rate. In table I, we show a comparison between the specifications (SPECS) and the performance of the SiPMs measured in Milano-Bicocca and Bologna laboratories. The results we present here are related to the SiPM selected for the FD-1: HPK S13360-9935 and FBK NUV-HD-CRYO TT [6]. Both the models are 6 mm×6 mm in size, with cell pitches of 75 μm and 50 μm, respectively.

Table I. – *SiPMs specifications and measured performance.*

	PDE [%]	SNR	DCR [mHz/mm^2]	Crosstalk [%]	Afterpulse [%]
Specs	> 35	> 4	< 200	< 35	< 5
FBK	45	7.2	86	16	3.2
HPK	45	6.0	65	9	1.1

4. – Cold and warm electronics

In order to obtain a large signal-to-noise ratio, it is essential to amplify the signal as close as possible to the SiPM. Therefore, the first amplification stage is implemented in liquid argon. The proposed solution for the DUNE FD1 is a cryogenic amplifier based on a silicon-germanium input transistor and a BiCMOS fully differential amplifier [5]. This design results in a SiPM signal with a rise time below 100 ns and a linear dynamic range extending up to 2000 photons at the typical operating voltage. Additionally, the low level of white noise enables a good single photoelectron resolution with an SNR >4.

DAPHNE (Detector Electronic for Acquiring Photons from Neutrinos) is the final stage of the PDS electronic chain. This board converts the analog signal into digital waveforms with a 14-bit resolution. It also provides the bias to the SiPMs and the power supply to the cold electronic. A single board streams data for 40 PDS channels with a sampling rate equal to 62.5 Ms/s.

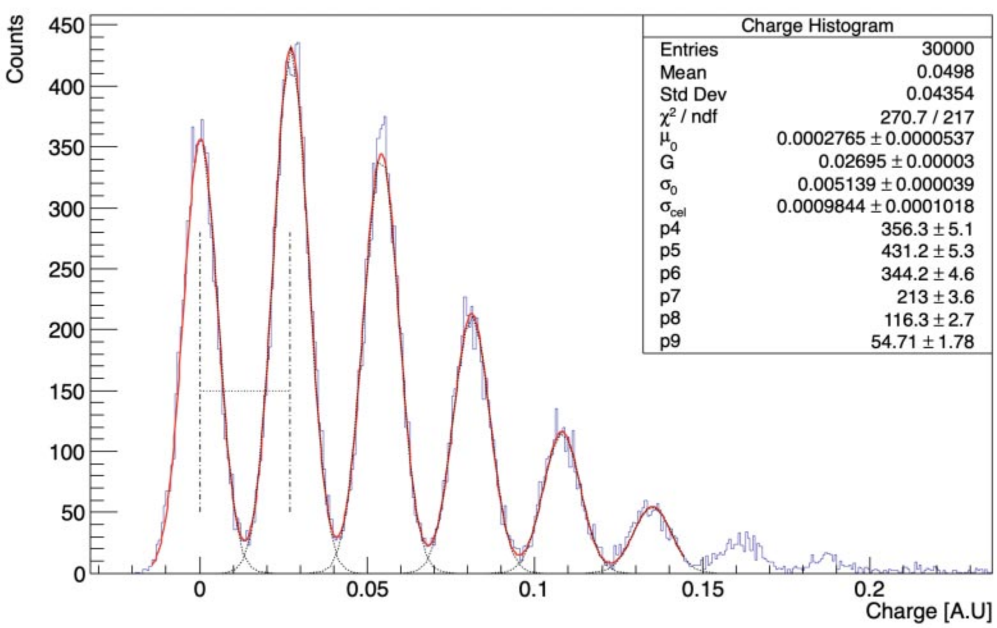

Fig. 2. – Calibration histogram. The signal-to-noise ratio is defined as the ratio between the gain (G) and the width of the zero photoelectron peak (σ_{cel}).

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