The DUNE photon detection system

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Summary. — The Deep Underground Neutrino Experiment (DUNE) beamline is composed of a powerful neutrino beam, monitored by a Near Detector (ND), and a Far Detector (FD). The accelerator and ND are hosted at Fermilab (IL) while the FD is located at the Sanford Underground Research Facility (SD), at a distance of 1300km. The FD is being built 1500m underground with a modular design. The first two modules will adopt the Liquid Argon Time Projection Chamber (LArTPC) technology and each module will have 17 kton total mass of liquid argon. The main physics goals are the determination of the neutrino mass hierarchy and a precision measurement of the CP-violating phase. In this paper, the Photon Detection System (PDS) will be described from the base module, XArapuca, up to the integration in the first two DUNE Far Detectors (FD1 and FD2).

1. – DUNE

The Deep Underground Neutrino Experiment [1] is a long baseline neutrino oscillation experiment with the main goals of determining the neutrino mass hierarchy and performing a precision measurement of the CP phase [2]. DUNE is composed of an accelerator complex and a Near Detector (ND) located at Fermilab in Illinois and a Far Detector (FD) located at the Sanford Underground Research Facility (SURF) in South Dakota, at a distance of 1300km. The accelerator will deliver a 1.2MW neutrino beam, the most powerful in the world, monitored by the ND, a complex of multiple detectors with the purpose of studying beam neutrinos and reducing systematic uncertainties.

The FD [3, 4] will monitor the neutrino and antineutrino beams to determine the oscillation probabilities. Being built 1500m underground, shielded from cosmic rays, it will also be able to study Beyond the Standard Model Physics such as baryon number violation as well as neutrinos from Supernovae (SNB) [5] and the sun. Fundamental for these studies is the Photon Detection System (PDS) providing the trigger from scintillation light.

2. – The Far Detector

The FD features a modular design granting flexibility, different systematic uncertainties between modules and the opportunity of employing new technologies in the future. The detector cavern can host up to 4 modules: the first two (FD1 and FD2) are based on Liquid Argon Time Projection Chambers (LArTPCs) and are now under construction, FD3 and FD4 are in R&D phase, the former being a further optimized LArTPC while for the latter different detector technologies are being evaluated.

2·1. *FD1 Horizontal Drift.* – The first FD module is designed to contain 17kton of liquid argon, divided in four 3.6m long horizontal drift volumes by two cathode planes and three anode planes. Two anode planes are placed along the long detector sides, observing one external volume each, the third anode plane is placed in the center of the detector, observing both the internal drift volumes.
The anode planes are modular, the base module is the Anode Plane Assembly (APA). The APA consist of four set of wires: one electric field shaping set, two induction sets and one collection set. The wires are winded with a 3mm spacing and with different angles to determine the charged particle track spatial coordinates perpendicular to the drift direction. The coordinate along the drift direction is obtained from the drift electrons time of flight given by the difference between time of production and arrival on the anode. The track ionization time is measured thanks to the scintillation light from the excited liquid argon, the drift electric field is set at 500V/cm so that the energy deposited by ionization from the charged particles is evenly distributed in scintillation light and drift electrons. The scintillation light is detected by the Photon Detection System modules placed inside the APAs, light is able to reach them thanks to the good transparency given by the winded wires design.

2·2. *FD2 Vertical Drift.* – The second module has the same dimensions of the first one and contains the same amount of LAr, it differs for the internal layout and charge collection design. In this module there are only two drift volumes divided by an horizontal cathode plane placed in the middle of the detector so that each volume has a vertical drift distance of about 6m.
The anode planes still present a four layer design but the wires are replaced by copper strips printed on perforated circuit boards. The base module of the anode is the Charge Readout Plane (CRP) and, compared to FD1 APA it is easier to produce and handle. Contrary to the APA, the CRP is opaque to the scintillation light so the PDS cannot be integrated into the anode. To be able to install the PDS modules on the cathode, systems to carry both signals as well as power to the modules have been developed: the Power Over Fiber (POF) delivers optical power, from a laser placed outside the detector, converted on the modules electronic board by an Optical Power Converter (OPC), signals generated by the PDS modules are read through the Signal Over Fiber (SOF) system.

3. – The Photon Detection System

The PDS task is to detect photons from LAr scintillation to determine the space coordinate perpendicular to the charge collection plane, trigger the data acquisition and perform light calorimetry. The main challenges are the detection of VUV light, absorbed by most optical grade components, and the required large surface to cover. In table I

TABLE I. – *DUNE Far Detector Photon Detection System requirements*

Description	Specification	Rationale
Light yield	> 20PE/MeV (avg.), > 0.5PE/MeV (min.)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $> 99\%$ of nucleon decay backgrounds with light at all points in detector.
Time resolution	$< 1\mu$s	Enables 1mm position resolution for 10 MeV SNB (Supernova Neutrino Burst) candidate events for instantaneous rate $< 1\text{m}^{-3}\text{ms}^{-1}$.
Spatial localization in the plane normal to the drift direction	< 2.5m	Enables accurate matching of PD and TPC signals.

some of the DUNE FD PDS requirements are reported [4]: both the specification and the rationale are shown i.e. an average light yield of more than 20 Photo-Electrons per MeV (PE/MeV) is required to be able to have a good energy resolution for low energy SuperNova neutrinos (SN νs) and to tag nucleon decay background.

To meet the requirement of a high Photon Detection Efficiency (PDE) over a large area, the XArapuca (XA) [6] device has been developed and implemented in the different FD modules. The XA is composed of a light-tight box with optical windows containing SiPMs coupled with a wavelenght shifting (WLS) PMMA light guide; the optical windows are coated on the external side with a WLS chromophore and, on the internal side, with a dichroic filter. The dichroic filter is a multilayer hard coating structure acting as a Fabri-Perot interferometer, its reflectance is dependent on the photon wavelength and incident angle. For the XA, the dichroic filter has a cutoff wavelength of 430nm so that light coming from the external chromophore (350nm) can enter the module while light coming from the internal light guide (450nm) is reflected back into the module.

The XA works as follows:

- 127nm Lar scintillation photons hit the optical windows and get downshifted to 350nm by the first wavelenght shifter
- 350nm photons are able to pass through the dichroic filters, entering the XA
- photons enter the light guide and are further downshifted to 450nm by the WLS dye embedded in the light guide
- if the emission angle is above the critical angle photons are trapped in the light guide, if it is below photons escape and are trapped by the dichroic filter
- trapped photons propagate towards the edges where they are detected by SiPMs

This efficient photon trapping and propagation mechanism allows to achieve a PDE of about 3% on the large area modules required by the DUNE Far Detector.

TABLE II. – *SiPM specifications*

Specification	HPK HQR 75μm	FBK NUV-HD-CRYO TT	u.m.
Active area	6x6	6x6	mm^2
Pixel pitch	75	50	μm
Breakdown Voltage	42	27	V
Selected OverVoltage	3	4.5	V
PDE @ Selected OV	50	45	%
Dark Count Rate	< 100	< 100	mHz/mm^2
Cross Talk probability	10.96	15.67	%
After Pulses probability	1.30	3.25	%

3˙1. *FD1-XA*. – In the first Far Detector module, the PDS is integrated into the APAs, this is possible because of the good optical transparency given by the anode wires. Each APA houses 10 PDS modules and each PDS module is composed of 4 optical channels read individually. An optical channel has dimensions of 50cm x 10cm x 1cm, it is equipped with 48 SiPMs uniformly distributed along the long edges. The light guides are produced by Glass to Power (G2P) while the SiPMs are produced by Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics K.K. (HPK) in equal parts.

3˙2. *FD2-XA*. – In the second Far Detector module, the PDS modules are distributed on the cathode, detecting light from both drift volumes, and on the side walls of the detector. The module has dimensions of about 60cm x 60cm, each module is equipped with 160 SiPMs distributed uniformly on all four light guide edges, read by two separate electronics channels; the optical coupling with the light guide is enhanced by springs pushing the flex circuits on which the SiPM are mounted.

3˙3. *Silicon Photon Multipliers*. – The SiPMs from both vendors are designed to operate at liquid argon temperature, have low Dark Count Rate (DCR) and high Photon detection Efficiency (PDE). These requirements are fundamental to be able to trigger on single photo-electons to be sensitive to low energy physics while keeping the data rate within the electronics bandwidth. After a selection procedure [7], one SiPM model per vendor has been chosen: NUV-HD-CRYO Triple Trench for FBK and HQR 75μm for HPK. In table II the specifications of the downselected models.

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