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The DUNE photon detection system

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Summary. — The DUNE Photon Detection System (PDS) is based on a novel cryogenic light-detector called X-ARAPUCA. It downshifts the 127 nm Liquid Argon (LAr) scintillation light and employs a dichroic filter to trap photons inside a reflective box, which is instrumented with Silicon PhotoMultipliers (SiPM) arrays. In this paper, we present a brief overview of the design and performance of the X-ARAPUCA, in view of the Run II of ProtoDUNE-SP at CERN. Furthermore, two X-ARAPUCAs were employed in Run I to validate the effectiveness of xenon as a LAr dopant against the quenching effect of nitrogen impurities. Preliminary results of this special run are also presented.

1. – Introduction

The Deep Underground Neutrino Experiment (DUNE) is a neutrino phyics experiment, currently in construction in the United States. It will consist of three main elements, shown in fig. 1. A high-intensity muon (anti)neutrino beam produced at the Fermilab Long Baseline Neutrino Facility (LBNF), will first cross a Near Detector (ND) [1] located 574 m downstream of the target, whose purpose is the reduction of systematic uncertainties by characterizing the beam, the detector response and the cross-sections of neutrino interactions. The (anti)neutrinos will then travel underground for ∼1300 km before impinging on a Far Detector (FD) [2, 3], located at the Sanford Underground Research Facility (SURF), that will detect the (anti)neutrinos. The ND and FD combined data will allow the measurement of the neutrino oscillation probabilities as a function of the neutrino energy in order to obtain the neutrino oscillation parameters, with a particular focus on the CP violating phase δ_{CP}, the mass hierarchy and the octant of the mixing angle θ_{23}. Furthermore, the DUNE FD will search for low energy non-beam events, namely supernova neutrino bursts and Beyond Standard Model events, such as the proton decay. In this paper we present a brief overview of the DUNE FD, focusing on the description of the X-ARAPUCA [4], the elementary unit of its photon detection

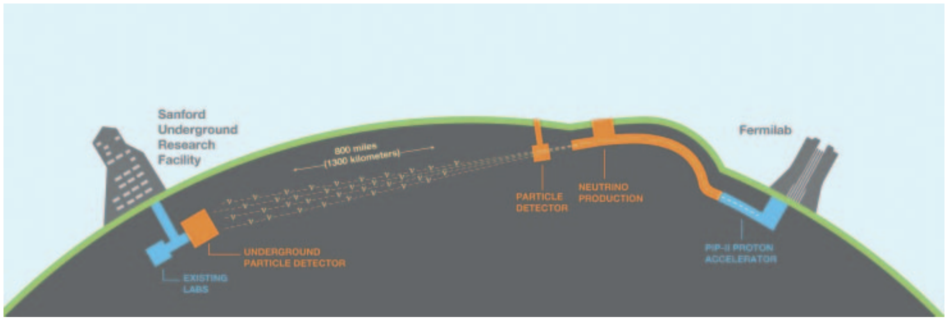

Fig. 1. – Schematic drawing of the DUNE project, highlighting its main components [2].

system. We report preliminary results of a xenon doping test campaign that was carried out in 2020 on ProtoDUNE Single Phase (PD-SP) [5, 6], the protoype of the DUNE far detector.

2. – The DUNE far detector

The DUNE FD will consist of four Liquid Argon Time Projection Chamber (LAr TPC) modules, each with a fiducial mass of at least 10 kt and a volume of approximately $14 \times 15 \times 62\,\mathrm{m}^3$. The LAr TPC [7] technology allows the detection of the products of ν-Ar interactions by measuring a charge signal and a scintillation one. The charge is collected by anodic wires and is used for tracking and calorimetric measurements. The scintillation light is detected by a dedicated Photon Detection System (PDS) and provides the precise timing of the event, triggering capabilities and a separate energy measurement. The 127 nm Ar scintillation light is emitted by excited Ar_2^* states, with a lifetime $\tau_s = 6$–7 ns or $\tau_t = 1.3\,\mu$s, depending on the molecular state. The DUNE FD will implement a modular PDS, composed of several unit cells named X-ARAPUCAs, which are described in sect. **3**. Currently two different geometries, defined by the direction of the drift of the charges, have been considered for the DUNE FD. In the Horizontal Drift (HD) [3] case, the PDS modules are located on the anode planes. The HD configuration has been tested in the first run of ProtoDUNE-SP and will be implemented in the first module of the far detector. In the Vertical drift (VD) [8] geometry, the PDS modules are situated on the cathode and lateral walls of the TPC. The VD configuration will be validated at CERN and used for the second module of the DUNE FD.

3. – The X-ARAPUCA light trap

The main challenge faced in the design of a PDS for the DUNE FD is represented by the need for a device that can operate in cryogenic conditions with a high Photon Detection Efficiency (PDE). In fact, most cryogenic photosensors have a very low PDE at 127 nm. The solution developed for the DUNE FD is the X-ARAPUCA light trap [4], the unit cell of the DUNE PDS. It consists of a box with highly reflective internal walls instrumented with an array of Silicon PhotoMultipliers (SiPMs). The entrance window is made up of two layers, the external one being Para-TerPhenyl (PTP), a WaveLength Shifter (WLS) that shifts the LAr scintillation light to $\lambda_{PTP} \sim 350$ nm. The window inner layer is a low-pass dichroic filter, with a cut-off at $\lambda_{CO} = 400$ nm. The photons emitted

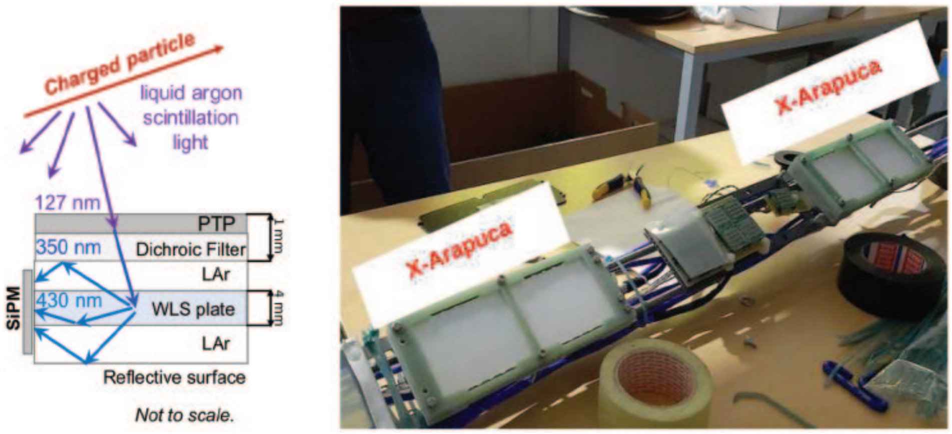

Fig. 2. – Left: schematic representation of the X-ARAPUCA working principle [10]. Right: picture of the two X-ARAPUCA prototypes employed for the 2020 test.

by the PTP cross the filter without being absorbed; inside the box they impinge on a WLS bar that is optically coupled to the SiPMs and shifts the light to $\lambda_{WLS} \sim 430\,\mathrm{nm}$. The photons then undergo total internal reflection inside the bar and are transported directly to the SiPMs. If photons escape the bar, they undergo multiple reflections on the dichroic filter (which now acts as a reflector) and the internal walls, until they are either absorbed or detected by one of the SiPMs. The two collection mechanisms are illustrated in fig. 2, left. The tests performed on various X-ARAPUCA prototypes yielded a light detection efficiency between 1.8 and 3.9% [9, 10], which is in line with the requirements for the DUNE physics goals.

4. – 2020 Xe doping run of ProtoDUNE-SP

Two X-ARAPUCA prototypes (shown in fig. 2, right) were tested for the first time inside the ProtDUNE-SP cryostat in 2020, during a run aimed at measuring the effect of xenon doping on the scintillation signal. The addition of small concentrations of xenon in LAr modifies the scintillation mechanism, as the Ar_2^* excimers transfer non-radiatively their energy to the Xe atoms, forming Xe_2^* excimers which decay radiatively, with the emission of 178 nm photons. This process competes with the quenching due to N_2 impurities in the argon [11]. Additionally, the Xe scintillation process results in a shorter (faster) signal and a longer Rayleigh scattering length. Tests of the Xe doping procedure have been performed in the past [12-16], on small scale detectors. In 2020, several Xe doping steps were performed on the ProtoDUNE-SP LAr volume, reaching a total of 18.8 ppm of Xe over the course of 5 months, testing the procedure for the first time in a large scale TPC. The evolution of the light signal produced by cosmic rays was monitored by studying the signals of the two X-ARAPUCA prototypes, along with those of earlier prototype PDS modules already installed in PD-SP. The 2020 Xe doping test allowed to verify the performance of the X-ARAPUCAs, which were also able to observe the evolution of the scintillation light signal caused by the Xe doping. Figure 3 shows the results of a preliminary analysis of such signals. Although further analysis is needed, the time profiles are compatible with those obtained from the other PDS modules, and qualitatively reproduce the expected shortening of the slow component of the signal.

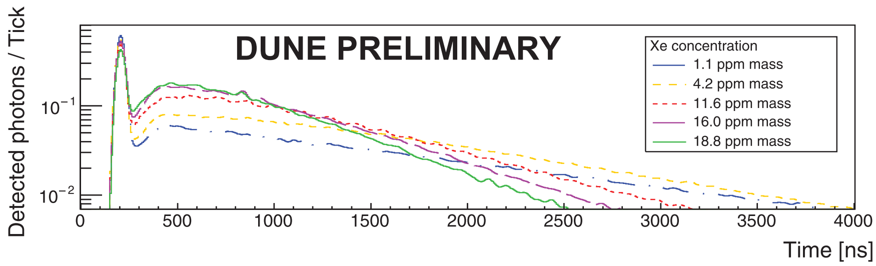

Fig. 3. – Average time profile of the scintillation light emission as a function of the Xe concentration (1 Tick = 6.667 ns). In order to obtain such a profile, a custom filter (analogous to the one presented in [17], minus the zero-area requirement) is applied to the X-ARAPUCA waveforms, to de-noise the signal and filter out the shape of the detector response. The filtered waveforms are then calibrated and averaged.

5. – Conclusions

In this article we presented a brief overview of light detection in the Deep Undeground Neutrino Experiment, with a focus on the X-ARAPUCA light trap. The first tests of the X-ARAPUCA protoypes resulted in a satisfying performance in terms of efficiency and two such devices were able to correctly operate for an extended period of time inside ProtoDUNE-SP. Furthermore, the X-ARAPUCA prototypes allowed to observe the evolution of the scintillation signal during a dedicated Xe doping run of ProtoDUNE-SP. The second run of this detector will implement a photon detection system composed of 40 X-ARAPUCA devices, in view of the construction of the DUNE FD.

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