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Xenon doping of Liquid Argon in ProtoDUNE Single Phase: first results

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Abstract. Doping Liquid Argon (LAr) with xenon is a known technique to shift the light emitted by argon (128 nm) to a longer wavelength to ease its detection. The largest Xenon doping test ever performed in a LArTPC was carried out in ProtoDUNE Single Phase (ProtoDUNE-SP) at the CERN Neutrino Platform. The response of such a large TPC (770 t of Liquid Argon and 440 t of fiducial mass) has been studied using the ProtoDUNE Photon Detection System (PDS) and a dedicated setup installed before the run. With the first, it was possible to study the light detected in the system as a function of the xenon concentration and to characterise the light collection efficiency with respect to the track position. With the second system it was possible to disentangle the LAr (128 nm) light from the xenon (178 nm) light using two dedicated X-ARAPUCA modules. The run was fully satisfactory, it was possible to measure directly the increase of the xenon light component during doping; furthermore most of the LAr light quenched by impurities was fully recovered even at small Xenon concentration (< 20 ppm in mass). A study of the collected scintillation light as a function of the track position showed an improvement of the detector response uniformity.

1. Introduction

The Liquid Argon Time Projection Chamber (LAr-TPC) has become an outstanding technology for rare event physics, ranging from neutrino oscillations to dark matter searches [1, 2]. This technology has reached such a level of maturity that it is possible to scale detector masses up to the multi-kiloton stage. DUNE (Deep Underground Neutrino Experiment) [3] will be the next-generation experiment for long baseline neutrino oscillation based on accelerators; it will perform precision measurements on oscillation parameters, investigate the neutrino mass hierarchy and CP-violation in the leptonic sector as well as non-beam related physics such as supernova neutrino bursts (SNB) and BSM (Beyond the Standard Model) searches. The DUNE far detector will consist of four LAr-TPC modules with 17 kt mass each that will be located at the SURF facility 1500 m underground.

Particles interacting inside the detector release energy by ionization; the produced electrons drift in an electric field and are readout by anode wires. In addition, LAr is an excellent scintillator with a photon yield around $\sim 24\,000$ ph/MeV at the DUNE nominal electric field of 500 V/cm. The light spectrum is peaked in the VUV (Vacuum Ultra Violet) range at 128 nm and is emitted through the de-excitation of singlet ($\tau_f \sim 6$ ns) and triplet ($\tau_s \sim 1.3\,\mu$s) states of Ar_2^* excited dimers. The detection of VUV light has some intrinsic difficulties but the advantages coming from it are important, especially for DUNE. It will give the absolute t_0

time of the interaction, improving the vertex reconstruction with respect to the information given by neutrino beam accelerator (1 cm → 1 mm). It is furthermore the only method to trigger events that are not produced by the beam such as SNB and BSM searches.

The DUNE Photon Detection System (PDS) can be enhanced by doping liquid argon with xenon at the level of a few ppm.[1] Ar_2^* excitation can pass to Xe, through energy transfer, producing Xe_2^* that eventually de-excites emitting 178 nm light. The longer wavelength of xenon light translates to a longer Rayleigh scattering length that improves the response uniformity of the detector. The triplet emission of xenon is much faster than argon, producing a faster time profile of signals. Furthermore the technique can be used to recover light quenched by pollutants, like N_2, as the Ar has a greater reaction rate constant with Xe than with N_2 [4]. Previous literature studies [5, 6] performed xenon doping of argon in small scale tests or gas mixtures, thus this is the first time ever the test is conducted in a full scale LAr-TPC like the ProtoDUNE Single Phase detector.

2. Xenon doping

Xenon is a noble cryogenic gas that liquefies at 165 K and freezes at 161 K, thus the injection procedure must be calibrated in order to avoid freeze-out effects. Tests in a small scale setup with a recirculation and purification system for argon have shown that a concentration ratio in the gas phase $\mathrm{Ar/Xe} > 10^3$ is needed to avoid freeze-out. Xenon is injected inside the detector through the argon recirculation system in the gas phase and far from the LAr condenser such that it can mix with gaseous argon before reaching the liquid phase. Considering numerical (CFD) simulation of the LAr flow inside the detector, the injected xenon is expected to be uniformly distributed within a few hours. Between February and May 2020 five different xenon injections were performed and in the mean time the detector performance was monitored. Each injection amounted to a few ppm, reaching a total amount of 18.9 ppm at the end of the doping procedure, corresponding to 13.5 kg of injected xenon.

Before the end of ProtoDUNE-SP Run 1 a sudden failure in the warm gas re-circulation pump leaked a certain amount of air inside the detector. Filters removed efficiently most of O_2 compounds but not nitrogen. The xenon doping run was conducted with a N_2 contamination estimated to be around 5.4 ppm. The N_2 reduces the triplet light component through collisional non radiative interactions with Ar_2^* ($Ar_2^* + N_2 \rightarrow 2Ar + N_2$).

3. ProtoDUNE Single Phase

ProtoDUNE Single Phase (Figure 1a) is the prototype of the first far detector module for DUNE. It consists of 770 t of LAr that is divided into two drift volumes, each having 3.6 m of drift length, by the Cathode Plane Assembly (CPA). The latter generates a uniform field of 500 V/cm to collect ionization electrons produced by charged particles interacting in the medium. The charge is readout by three planes of wires that are organized in Anode Plane Assemblies (APA). ProtoDUNE-SP worked as a test bench for next-generation LAr-TPC technologies and for their R&D; its response has been studied with a beam of different particles (π, K, μ, e) and with cosmic rays [7]. The xenon doping run presented here is part of this effort before the end of operations for re-commissioning.

3.1. Photon Detection System

Scintillation light is collected through Photon Detection System (PDS) modules that shift the 128 nm photons to a detectable wavelength for Silicon PhotoMultipliers (SiPM). Ten PDS modules equally spaced on the vertical direction are installed into each APA (Figure 1b). Three different types of light collectors [7] are present in ProtoDUNE-SP: dip-coated light guides,

[1] In this paper we consider every concentration in ppm (part per million) expressed in terms of mass.

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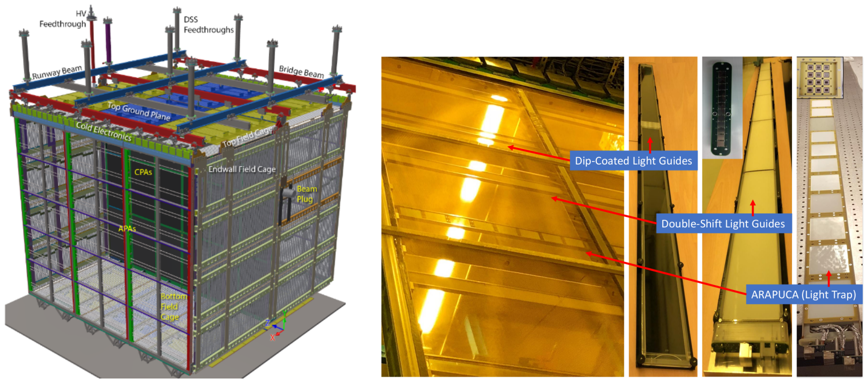


(a) (b)

Figure 1: (a) 3D view of ProtoDUNE-SP. (b) PDS modules installed inside an APA frame.

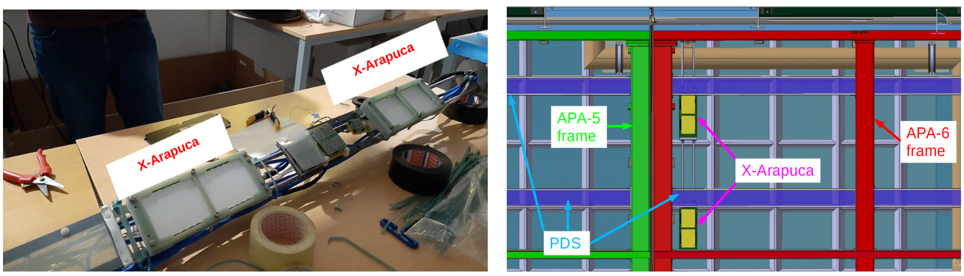
double shift light guides and ARAPUCA. The ARAPUCA detector is the chosen technology for the DUNE far detectors. It consists of a reflective box closed on all sides but one, where a dichroic filter is placed. The filter is coated externally with pTP (P-Terphenyl) to shift LAr light to 350 nm where it is transparent, the shifted light passes through the filter and is shifted by an internal layer of TPB (Tetraphenyl Butadiene) to 440 nm at which the filter is reflective. Trapped photons are finally detected by SiPMs placed on the side of the box.

With the PDS it is possible to analyze a sample of horizontal crossing muons, parallel to the photon detectors, that are triggered with a Cosmic Ray tagger (CRT) [7] installed on opposite sides of ProtoDUNE-SP. It consists of scintillator strips ($5\,\text{cm} \times 365\,\text{cm}$) that are arranged in two orthogonal layers, allowing the trigger and position reconstruction of the tracks.

3.2. Dedicated X-ARAPUCA setup

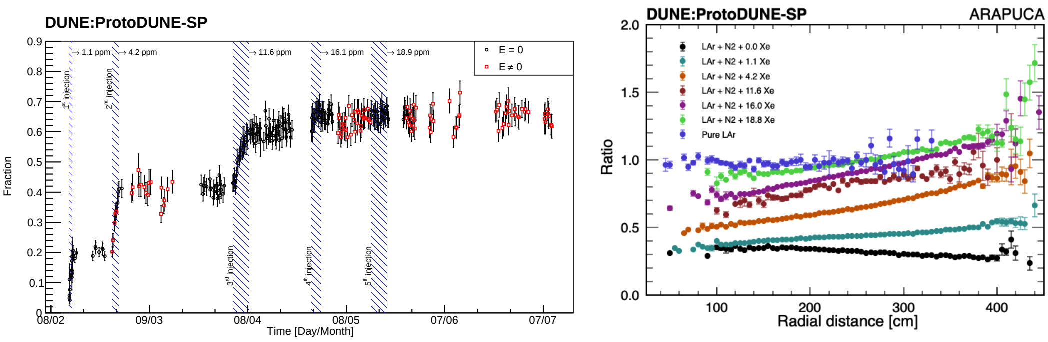
A dedicated setup was inserted in ProtoDUNE-SP to disentangle the xenon effect on the total light emission. Two X-ARAPUCA modules (Figure 2), the upgraded version of the ARAPUCA where the internal TPB is substituted by a WLS (wavelength shifting) bar, were located behind one of the APAs of ProtoDUNE-SP. The two X-ARAPUCA, named supercells, are intrinsically sensitive to both Ar and Xe light, thus the first cell is equipped with a 2 mm fused silica window in front of it so that only the 178 nm light could pass through. The first supercell is referred to as “Xe XA”, as it detects only Xe light, while the second one as “Ar+Xe XA”.

The system exploited a standard triple coincidence of plastic scintillators to select a sample of vertical cosmic muons that crossed the TPC in front of the X-ARAPUCA supercells.



(a) (b)

Figure 2: (a) Dedicated setup with two X-ARAPUCA: on top sensitive only to Xe light. (b) Sketch of the installation of the setup.



(a) (b)

Figure 3: (a): Fraction of converted light (128 nm → 178 nm). Shaded areas show xenon injection periods. (b) Ratio of collected light relative to the pure LAr (no N_2 contamination).

4. Results
The efficacy of the xenon doping mechanism can be tested measuring the amount of shifted light with respect to the total light detected. This observable, called Fraction (Eq. 1), is measured as the ratio of the average light detected by "Xe XA" with respect to the one of "Ar+Xe XA".

$$\text{Fraction} = \frac{\text{Xe light}}{\text{Ar light} + \text{Xe light}} \equiv \frac{\langle \gamma_{\text{Xe XA}} \rangle}{\langle \gamma_{\text{Ar+Xe XA}} \rangle} \tag{1}$$

The Fraction (Figure 3a) increases with each doping and it tends to settle around 0.65 for xenon concentration greater than 16.1 ppm.

The response of the entire detector can be understood using the ratio of the collected light relative to the pure LAr as a function of the track distance. The latter quantity (Figure 3b) shows that the accidental N_2 contamination reduced scintillation light yield by more than a factor 2, and the injection of xenon recovered the light. The slope of the curves increases with the xenon concentration, indicating a more uniform light collection as the collection efficiency far from the detection point increases.

5. Conclusions
In this paper the first large scale xenon doping of liquid argon was presented; the TPC (770 t) was safely operated up to $\sim$ 20 ppm of xenon concentration. The response of the detector was monitored with a dedicated X-ARAPUCA setup and with the Photon Detection System of ProtoDUNE-SP. The wavelength shifting mechanism (128 nm → 178 nm) was proved to be effective already at few ppm and tends to settle at $\sim$ 16 ppm. The study conducted with respect to the distance between the track and the photon detectors confirms that the majority of the light loss due to N_2 contamination is recovered by xenon; furthermore the response of the detector is more uniform as the increased light collection efficiency far from the detection point confirms a longer Rayleigh scattering length for 178 nm photons.

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