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Performance of the $3 \times 1 \times 1$ m^3 Dual Phase Liquid argon TPC

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Liquid Argon Time Projection Chamber (LAr TPC) is currently one of the most attractive technologies for neutrino oscillation studies. Not only LAr TPCs are cost-effective and scalable to multi k-ton scales, but they are also excellent calorimeters and are able to 3D reconstruct the tracks of ionising particles arising from neutrino decay products. Future giant liquid Argon TPCs, at the scale of tens of k-ton level, are now at the design and prototyping stage in the context of the Deep Underground Neutrino Experiment (DUNE). DUNE will comprise four 10 kton LAr TPC modules placed at the Sanford Underground Research Facility (SURF) in South Dakota (USA). Two different technologies will be tested: single phase and dual phase. The dual phase TPC operation allows to amplify and readout the signal offering several advantages over the single phase. The first step towards large scale Dual-Phase LAr TPCs has been the commissioning and operation of a $3 \times 1 \times 1$ m^3 detector at CERN with 4.2 tons of Argon. The construction, commissioning, performance and first results achieved with this detector will be addressed.

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1. Introduction

The Deep Underground Neutrino Experiment (DUNE)[1] is part of the next generation of long-baseline neutrino experiments aiming to search for the leptonic CP violation and determine the ordering of the neutrino masses. The Far Detector will be based on liquid Argon Time Projection Chamber (LAr TPCs) technology and will consist of four modules each with 10 kton of LAr. In a LArTPC, charged particles ionise the liquid argon, producing electrons that are drifted and induce signals inside the liquid (single phase (SP)) or are extracted to the gas phase where they are amplified and collected on readout anodes (dual phase (DP)). To study the feasibility to operate giant LAr TPCs two prototypes of each technology were constructed at CERN. The dual-phase LAr TPC is an innovative technique where the attenuation of the charge after drifting several metres is compensated by the amplification of the charges inside the gas phase [2]. The electron drift time and the collected charge allows to precise 3D reconstruction of the track and excellent energy resolution. A prototype detector with an active volume of $3 \times 1 \times 1$ m^3 was built in 2016 and operated in 2017 at CERN to test the feasibility of this technology at the tonne scale. A summary of the technical description and performance of the demonstrator can be found in [3].

2. Overview of the $3 \times 1 \times 1$ m^3 and the dual phase principle

The experiment consists of a $3 \times 1 \times 1$ m^3 (4.2 t) active volume dual-phase LAr TPC embedded inside a non-evacuable membrane cryostat of ~ 23 m^3 internal volume with one meter passive insulation. It was the first cryostat designed and constructed by GTT, the same company which built protoDUNE-SP and protoDUNE-DP, under construction and operation at CERN, and DUNE far detectors. The detector is suspended from the *top-cap*, a 1.2 m thick insulating lid which reduces the heat input, minimizes the convection of the liquid and gas argon, incorporates all the interfaces to the cryogenic system and all the required feedthroughs for signal, high voltage and slow control sensors.

When an ionising particle traverses the LAr, the electrons produced after the interaction with the argon nuclei drift vertically towards the liquid-vapour boundary where they are extracted into the gas phase, amplified by the Large Electron Multipliers (LEMs), and collected on finely segmented anodes. The electron extraction, amplification, and collection are performed inside the *Charge Readout Plane (CRP)*, an electrically and mechanically independent 3×1 m^2 frame. The LEMs and anodes are manufactured in units of 50×50 cm^2 which are assembled together to cover the whole area. The anodes are electrically bridged together to provide two orthogonal sets of readout strips, one on of three metre long, *view0*, and another of one meter long, *view1*.

The scintillation light from argon excimer produced after the interacting particle traverses the liquid is detected by five photo-multiplier tubes (PMTs) mounted underneath the TPC drift cage. It defines the absolute time of the event and provides the trigger for the data acquisition system. Two Cosmic Ray Taggers (CRT) are located on the sides to trigger on quasi-horizontal muons traversing the full three meter length of the detector. Apart from the primary scintillation, S1, the PMTs are also sensitive to the secondary scintillation light (S2) from the electroluminescence of the electrons extracted in the argon vapour.

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3. First results from the prototype

The entire operation period (including commissioning, tests and data taking in several high voltage configurations) of the prototype started in June until mid November 2017. During this period, the liquid surface was stable as required for detector operation. We achieved an excellent liquid argon purity and high voltage operation of the cathode allowing to drift the electrons stably at 500V/cm. Moreover, the primary (in liquid) and secondary (in gas) scintillation light were observed and we collect in total 5×10^5 events. However, due to technical limitations of the operating potential of the extraction grid and the maximum voltage reached on the 50×50 cm^2 LEM we could not operate the TPC at an effective gain of 20. Around 30000 cosmic events were collected in the run with the best high voltage settings which provide a large extraction efficiency and some amplification inside the LEMs. These settings were: top, bottom LEM electrodes and the extraction grid are biased to -0.3, -3.1 and -5kV providing an induction, amplification and extraction field in the liquid of 1.5, 28 and 1.7kV/cm, respectively. From this run a sample of cosmic muons which cross the TPC are selected and analysed to estimate the free electron lifetime, the amplification in the LEMs and the charge sharing between views.

Fig.1 shows the distributions of the collected charge per unit length as a function of the electron drift time (t_{drift}) for both views. The average energy loss as a function of the drift time is described by the exponential law e^{-t_{drift}/τ_e}, that accounts for charge losses due to electron attachment to impurities. The mean electron lifetime τ_e retrieved by fitting the data in both views (black line), indicates an electron lifetime better than 4ms, which corresponds to an oxygen equivalent impurity of less than 75ppt.

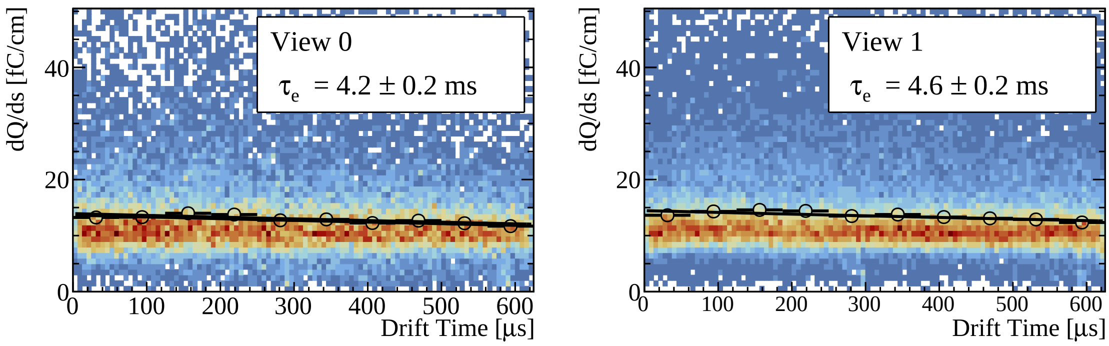

Figure 1: The scatter plot shows the collected charge per unit length in each view as a function of drift time for through-going muons.

The performance of the extraction, amplification, and collection stage is described by the effective gain, G_{eff}, which accounts the multiplication of the electrons inside the LEM holes and the overall electron transparency of the extraction grid, LEM, and anode. To estimate the achieved value in the demonstrator and verify the 50% charge sharing between views the shapes of the $\Delta Q/\Delta s$ distributions for both views corrected for the electron lifetime have been analysed. Their shapes are described by a Landau function with a Gaussian smearing as expected from the fluctuations of the collected charge per unit length. The effective gain of the TPC is defined as the sum of the charge collected per unit length in each view divided by the deposited charge of a minimum ionising particle (MIP):

$$G_{eff} = \frac{\langle \Delta Q_0/\Delta s_0 \rangle + \langle \Delta Q_1/\Delta s_1 \rangle}{\langle \Delta Q/\Delta s \rangle_{MIP}} \tag{3.1}$$

For a MIP track, the average charge deposited per unit length is described by the Bethe-Bloch formula and is about 10fC/cm. By taking the mean of the distributions in Fig. 2 we obtain a preliminary estimation of $G_{eff} \approx 3.5$, a value obtained before complete charging up of the LEM modules. From the distributions we also appreciate that there is no large asymmetry in the charge collected by each view.

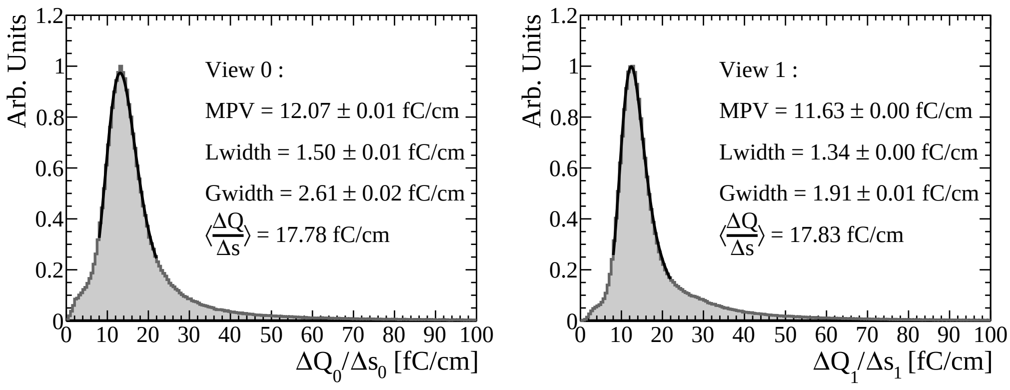

Figure 2: The $\Delta Q_0/\Delta s_0$ and $\Delta Q_1/\Delta s_1$ distributions for both views for selected straight tracks (see text for more details).

4. Conclusions

The $3 \times 1 \times 1$ m^3 demonstrator has opened the path towards large DP LAr TPCs. Although the performance was limited by the extraction grid maximum voltage, more than 500k events were collected. It has been the first time that extraction efficiency over a 3 m^2 surface and amplification with large area LEMs of 50×50 cm^2 has been demonstrated. In addition, it has opened the path towards membrane tanks to host LArTPC. The $3 \times 1 \times 1$ m^3 has been the first LAr TPC operated in a membrane tank and has shown an excellent performance of the cryogenic system with a purity compatible with ms electron lifetime. Many detector components were fully engineered versions of protoDUNE-DP allowing to gain a large experience for the design, installation and commission of future larger devices.

References

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