Study of Light Production With A Fifty Liter Liquid Argon TPC

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Abstract. The Deep Underground Neutrino Experiment (DUNE) is the next very large scale neutrino science and proton decay experiment. DUNE will consist of large-scale near and far detectors. The core elements of these detector systems are liquid argon Time Projection Chambers (LAr TPCs) and light readout systems. Two prototype far detectors were built and operated at CERN Neutrino Platform and extensive developments are underway for improved and upgraded detectors. In order to evaluate various design alternatives and validate new concepts of light readout related to large-scale LAr detectors, we have performed several experiments with a fifty liter liquid argon TPC at CERN. Among the long list of configurations we probed, study of various wavelength shifters, operation in dual phase mode and Xe and N_2 doping under different scenarios can be listed. Here we report on the details of the various test campaigns and discuss our findings and their impact on the design and operational parameters.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) [1] is a next-generation, long-baseline neutrino oscillation experiment, with a near detector at Fermilab and a far detector located at Sanford Underground Research Facility (SURF), in Lead, South Dakota, U.S.A., 1285 km from the neutrino production target. The far detectors will be at the 4850 ft level of SURF and will be housed in four large cryostats which will contain 17.5 kt of liquid argon (LAr). The detectors will employ various technologies such as horizontal and vertical drift time projection chambers (TPCs) and novel photon detection systems. Two large-scale prototype detectors were constructed and operated at the CERN Neutrino Platform [2] in the course of the past few years and various results were established [3-6]. LAr TPC technology and dedicated light readout systems are presently well-established and are continuously developed by several neutrino and dark matter experiments (see e.g. [7] and [8]).

Performing R&D on liquid argon TPCs and light detection systems requires a well-established infrastructure that would allow reliable and safe operations of cryogenic systems; and flexible and efficient detector and readout systems for an effective collection of data. We performed several R&D experiments with a fifty liter LAr TPC, among which the study of various wavelength shifters, operation in dual phase mode, and Xe and N_2 doping under different scenarios can be listed. The fifty liter LAr TPC at CERN provides a very effective R&D environment to quickly validate new ideas and to address emerging problems in large-scale systems. Here we report on a few of the experiments and present preliminary results.

2. Fifty Liter LAr TPC

The fifty liter LAr TPC is constructed as a hanging structure from a custom made flange to be placed as a cap on a custom made dewar. The top of the chamber houses many feedthrough and instrument flanges which can be modified for specific experiments. Examples include the signal and high voltage feedthroughs, and special flanges for pressure transmitters, temperature sensors, cameras and safety devices.

The TPC has three wire planes each of which contains 128 wires of 2.54 mm pitch. The wires are 325 mm long and the wire planes are separated by 4 mm. Screen grid wires are parallel to the induction wires. 128 induction and 128 collection wires are read out by CAEN A2795 modules [9]. The drift distance is 52 cm. The field cage is formed by 25 squared rings made out of uncoated, extruded 10 mm × 10 mm aluminum bars. The rings have 10 mm spacing and the voltage divider is provided with a parallel connection of three 50 MΩ resistors at each stage. Four vetronite bars hold the rings together. The cathode is a resistive layer of Kapton lamination and the nominal drift voltage is 500 V/cm.

During assembly, the top flange is placed on a square frame and the chamber can be instrumented from any direction. Once all the room temperature tests of the detectors and the sensors are completed, the instrumented flange is placed on top of the test dewar using an indium wire as sealing material. The average vacuum level in 24 hours is 10^{-7} mbar. The cooldown and filling with the purified LAr usually takes around 6 hours. Afterwards, the chamber can be operated for several weeks without problems. Since there is also an integrated boil-off gas recirculation system, the purity of LAr improves gradually, following the initial fill. Online and offline event displays with 3d track reconstruction, slow control and pressure and temperature monitoring tools were developed in order to monitor the performance of the chamber online during the operations and also offline.

3. Tests with the Wavelength-Shifter and Reflector Foil on the Cathode

In three test campaigns, we tested the performance of a reflective foil coated with tetraphenyl butadiene (TPB) (denoted as *Run 1*) and a reflective foil with a polyethylene naphthalate (PEN) sheet (denoted as *Run 2*) placed on top of the cathode, against the plain cathode (denoted as *Run 3*). The TPB coating of the reflective foil was done in University of Manchester.

Various cosmic muon trigger configurations were used during the tests. The drift velocities and the electron lifetimes were measured with muons crossing the entire drift distance. Figure 1 (left) shows the electron drift velocities measured for the three test campaigns. Fits to constant values across each test campaign yield 0.148 cm/ms for *Run 1*, 0.147 cm/ms for *Run 2* and 0.150 cm/ms for *Run 3*. The effective high voltage calculated for *Run 1* and *Run 2* based on these drift velocities are approximately 5 % less than the nominal high voltage of *Run 3*.

Figure 1 (right) shows the electron lifetime measured during *Run 3*, and this trend is typical also for the other campaigns. The electron lifetime starts around 400 ms with the initial fill and approaches 1

Journal of Physics: Conference Series **2374** (2022) 012165 doi:10.1088/1742-6596/2374/1/012165

ms level with recirculation. The improvement can also be tracked with the online event display visually.

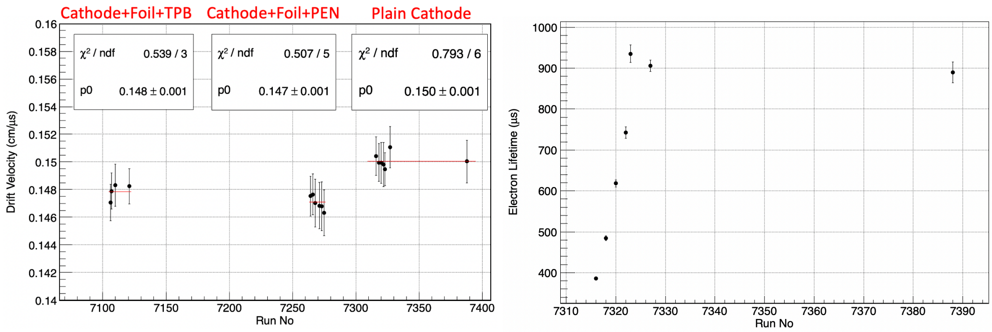

Figure 1. Electron drift velocities measured in the three test campaigns (left) and the electron lifetime measured during *Run 3* (right).

During the tests, two PMTs were used to measure the light yield: Hamamatsu R11065 PMT with TPB coated window (denoted as *LAr w/TPB*) and Hamamatsu R11410 which is more sensitive to the Xe scintillation light (denoted as *LXe*) [10]. The single photoelectron (spe) responses of the PMTs, shown in Fig. 2 left three plots, were continuously monitored during each test campaign and were found to be stable apart from the cooldown period and some obvious modifications such as the high voltage changes during Run 1 indicated with red dashed lines.

The slow component of LAr scintillation was also monitored as it is an indication of the purity of the LAr in addition to the electron lifetime. Figure 2 (right) shows the slow components measured with *LAr w/TPB*, and the values range between 1.4 ms and 1.6 ms.

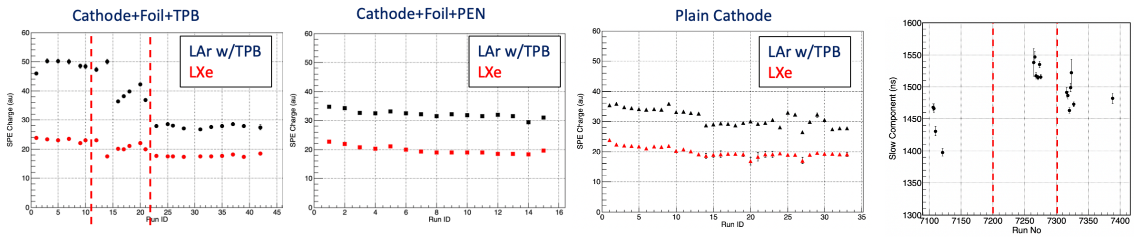

Figure 2. Single photoelectron response of the PMTs across the three test campaigns (left three plots) and the slow component of LAr scintillation (right plot, the red dashed lines separate the three test campaigns).

Figure 3 shows the light yield measured with the *LAr w/TPB* (left) and *LXe* (right) for the three test campaigns. The number of photoelectrons per cm is calculated using minimum ionizing particle (MIP) tracks traversing the full drift distance. This was then converted to the number of photoelectrons per MeV considering an energy loss per MIP of 2.1 MeV/cm. For the measurements with *LAr w/TPB*, the increase in light yield is 17 % with PEN and 45 % with TPB compared to the plain cathode response. The relative wavelength shifting efficiency of PEN/TPB is measured to be approximately 38 %, and is consistent with the recent similar measurements [5, 11]. For the measurements with *LXe*, 86 % of relative increase in light yield with TPB compared to PEN was measured. The nonzero response of *LXe* with plain cathode is expected to be due to the reflections of the light shifted by the TPB coating of the *LAr w/TPB*. The effect of this reflection, together with the effect of the transmission of visible light through the TPB coating of the *LAr w/TPB* is under investigation with Monte Carlo simulations.

The response of the fifty liter LAr TPC is simulated with Geant4 [12]. Identical track parameters are provided to the simulation, and the ionization locations and the Cerenkov and scintillation light collected at the PMT locations are recorded. The PMT signal is then reconstructed using the generic

Journal of Physics: Conference Series **2374** (2022) 012165 doi:10.1088/1742-6596/2374/1/012165

quantum efficiency curves provided by Hamamatsu. The only tuning of the simulation is done with the plain cathode setup and implemented as a single factor on top of the reconstructed response in order to account for the differences in the actual quantum efficiency curves of these particular PMTs. In the first results, the main response is reproduced, but the tail is not reproduced well, which is due to the suppressed production of the delta rays along the MIP tracks in the simulations. Alternative Geant4 electromagnetic physics lists are being studied.

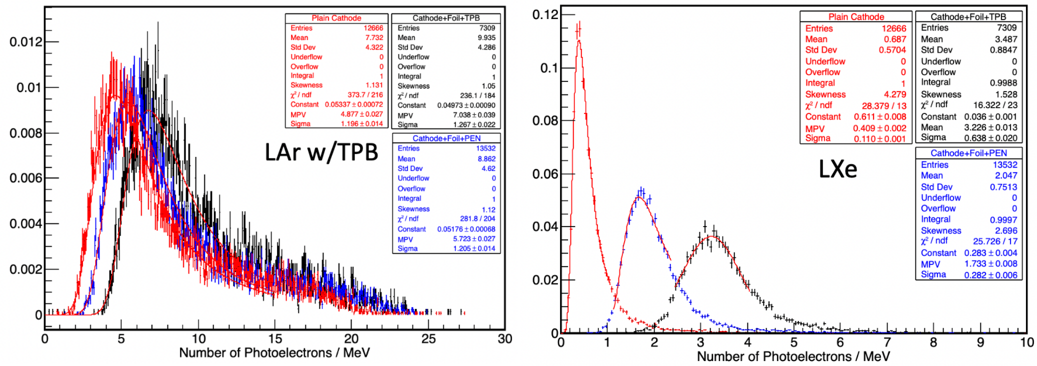

Figure 3. The light yield measured with the *LAr w/TPB* (left) and *LXe* (right) for the three test campaigns.

4. Dual Phase Xe Doping

In order to investigate the effect of Xe doping in a dual phase TPC, we established a dedicated test setup. In addition to the two PMTs used in the wavelength-shifter studies, the setup included a Hamamatsu R11065 PMT with clean window (denoted as *LAr no TPB*). The drift distance was 12.5 cm and the nominal drift voltage was 500 V/cm. The extraction region was 2 cm and the liquid level was kept at the center. The extraction field was varied between 3 kV/cm and 3.5 kV/cm during the tests. The events were triggered with two scintillation counters on top of the chamber for cosmic muons crossing the entire drift distance. There was no charge readout in this configuration. The Xe injection was done at four sessions to obtain 25 ppm, 50 ppm, 100 ppm and 200 ppm.

Figure 4 (left) shows the average waveforms of the three PMT signals at 50 ppm of Xe concentration for 1.5 ms. The waveforms were fit to $ae^{-(t-t_0)/\tau_1} - be^{-(t-t_0)/\tau_2} + ce^{-(t-t_0)/\tau_3}$, where τ_1, τ_2, τ_3 are fast, transfer and slow components. As expected, the slow component is reduced dramatically with Xe doping and at 50 ppm it is approximately 110 ns.

5. N_2 Injection and Xe Doping

The ProtoDUNE-SP detector was contaminated with N_2 at around 5 ppm level, which degraded the performance of the light readout systems; and a mitigation with Xe doping was planned. In order to investigate the necessary Xe concentration to dominate the decreased light output, we established a controlled contamination and doping experiment with the fifty liter LAr TPC. The drift distance for this configuration was 12.5 cm with a nominal high voltage of 500 V/cm. In addition to the PMTs in the dual phase Xe doping test, the chamber also contained an R11065 PMT with its window newly coated with TPB (denoted as *LAr w/TPB new*). The events were triggered with two scintillation counters on top of the chamber for cosmic muons crossing the entire drift region. The particularly challenging N_2 concentration was achieved in several injections spanning several days with careful evaluation of the slow component of scintillation after each injection. Starting at approximately 1.2 ms, a slow component around 700 ns is reached at 5.2 ppm N_2 concentration.

Figure 4 (center) shows the average response measured with various PMTs during the N_2 injections and the Xe doping. *LAr w/TPB* response drops to approximately 70 % of its initial value with 5.2 ppm of N_2 contamination (*LAr w/TPB new* performance was not validated and can only serve for qualitative comparison). All PMTs see an increase in the level of light with Xe doping as a sharp step at the beginning of the doping with a rather slow increase with increasing Xe concentrations. Figure 4 (right) shows the average waveforms with the three component exponential fits for all the PMTs at 5.2 ppm N_2 + 20 ppm Xe concentration. The slow and transfer components have comparable values around 400 ns at this concentration level.

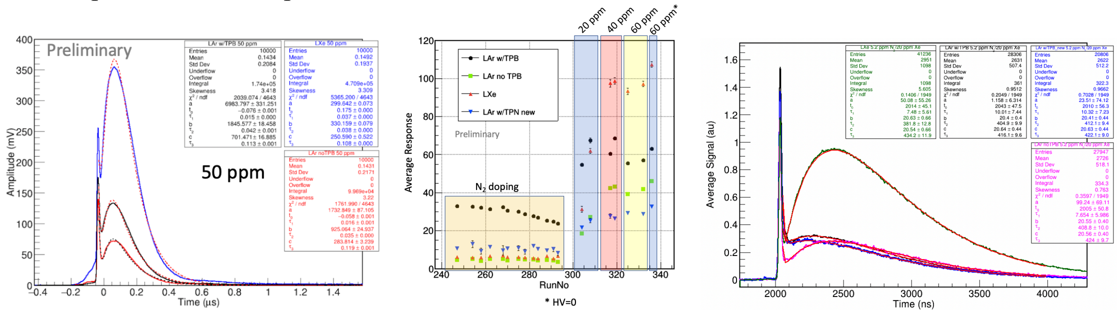

Figure 4. The average waveforms of the three PMT signals at 50 ppm of Xe concentration in dual phase setup (left); the average response measured with various PMTs during N_2 injections and Xe doping (center); the average waveforms of all the PMTs at 5.2 ppm N_2 + 20 ppm Xe concentration (right).

6. Conclusions

The fifty liter liquid argon TPC at CERN is a valuable R&D equipment offering flexible chamber configuration, simple and reliable operations of the cryogenic systems, and fast and effective operations of the detectors.

We performed several experiments yielding large amounts of unique datasets. We tested the performance of reflective foils coated (laminated) with TPB (PEN). The effective high voltage was measured to be reduced around 5 % with the introduction of the foils. The light yield increase compared to the plain cathode is 45 % (17 %) with TPB (PEN).

We did several N_2 injection and Xe doping tests. The quenching effect of N_2 is eliminated by Xe doping starting from very small concentrations. A three component exponential fit to the average waveforms of light signals seem to represent the data well. The chamber was also operated at the dual phase mode for several days.

Data analysis and simulation studies to combine the results across various test campaigns are underway.

Acknowledgements

B. Bilki, F. Boran and F. Dolek acknowledge support under Tübitak grant no 118C224. The work of M. Babicz was supported by the National Science Center, Poland, research project No. 2019/33/N/ST2/02874. A. M. Szelc received funding from the Science and Technology Facilities Council (STFC), part of the United Kingdom Research and Innovation; and from the Royal Society UK awards: RGF\EA\180209 and UF140089.

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