Commissioning and beam test of a high pressure time projection chamber

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Time Projection Chamber · High Pressure Gas · Optical Readout · Neutrino oscillations · Near Detector

Abstract

Due to their large active volume and low energy threshold for particle detection Time Projection Chambers (TPCs) are promising candidates to characterise neutrino beams at the next generation long baseline neutrino oscillation experiments such as DUNE and Hyper-K. The higher target density for the incoming neutrino beam of a TPC filled with gas at High Pressure (HPTPC) will potentially allow for better neutrino-nucleus interaction measurements as compared with TPCs at atmospheric pressure.

The HPTPC we built has an active volume of about $0.5\,\mathrm{m}^3$ which is embedded into a pressure vessel rated up to 6 bar absolute pressure. A cascade of three meshes amplifies the primary ionisations. The induced charge on each mesh is read out. In addition the photons emitted during the gas amplification are read out by four CCD cameras focused on the readout plane, which thus image the 2D projection of a particle's tracks on the transverse plane. The third coordinate is reconstructed from the charge signal.

We tested the HPTPC's performance during a four week beam test at the CERN PS, measuring low momentum proton ($\leq 0.5\,\mathrm{GeV}$) interactions with the counting gas. Several mixtures with Argon predominance have been tested for their light yield and gas gain. The aim is to calculate the proton-Ar cross-section from the data sample, which will enter the calculations of final state interactions in neutrino Ar scattering.

1 Introduction

The aim is to develop the physics case for, and the technological readiness of, a High Pressure Time Projection Chamber (HPTPC) as a neutrino (ν) detector for accelerator neutrino oscillation searches. We have therefore commissioned a prototype HPTPC with optical readout in order to demonstrate its feasibility and to perform new measurements of proton and pion scattering on Ar.

At Long BaseLine (LBL) neutrino experiments such as the Tokai-to-Kamioka experiment (T2K) gas filled TPCs [1] serve as part of the *near detector*, which characterises the neutrino beam before it undergoes oscillations on its several 100 km long way to the far detector. In the detector neutrinos undergo a charged current interaction with a nucleus and thus produce Final State Interaction (FSI) particles. Gas filled TPCs are well suited to measure FSI particles of ν-Ar nucleus interactions, thanks to their low momentum threshold for particle detection and their $4\,\pi$ coverage. For such measurements the gas serves as target and detection medium.

The motivation for a high pressure gas TPC is to improve the measurement of FSIs. Ultimately, the goal is to achieve 1-2 % systematic error on ν-nucleus scattering for oscillation measurements at 0.6 GeV and 2.5 GeV neutrino energy, as required for the charge-parity violation sensitivity projections by the Hyper-Kamiokande [2] experiment (Hyper-K) and the Deep Underground Neutrino Experiment (DUNE) [3]. The FSI uncertainties in neutrino-nucleus interactions dominate cross-section systematic errors and are currently about 5–10 % at these neutrino energies. Therefore research and development on new technologies is required, to achieve a substantial improvement of these uncertainties.

The target density increases with the gas pressure and therefore a HPTPC will measure more interactions while retaining at the same time the advantages of a gas filled TPC. Furthermore a HPTPC can be used to measure proton (pion) nucleus scattering – in addition to a future application at an LBL neutrino experiment – and employ these results to improve the uncertainties of the nuclear-models used in neutrino Monte Carlo generators. For example two popular generators,

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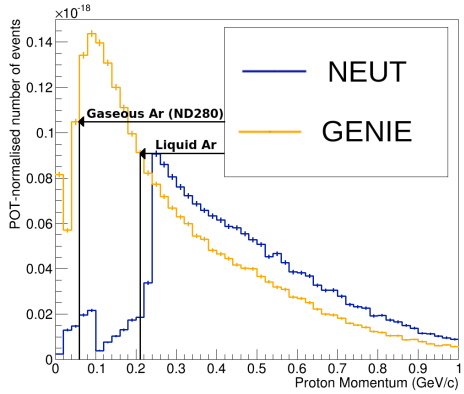


Figure 1: Simulation of the proton momentum distribution for final state interactions after ν_μ charge current interactions on Ar [4].

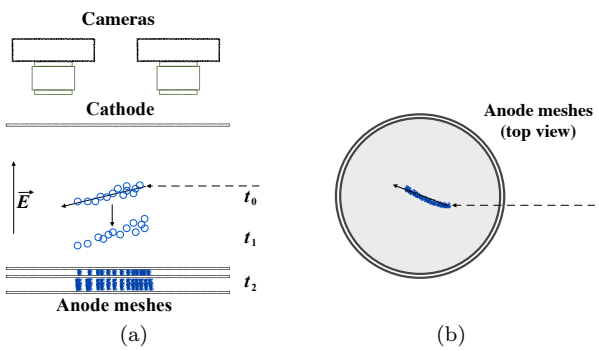


Figure 2: Cross-sectional sketch of the HPTPC through the (a) xz plane and the (b) xy plane. At a time t_0 a particle scatters on a gas atom, ejects a proton which ionises gas atoms (circles, Fig. (a)) along its path. These ionisation electrons drift in the electric field E towards the anode meshes (t_1) and are amplified at $t = t_2$. The photons produced during the avalanches (thick lines, Fig. (a)) can then be imaged by the cameras and provide a 2D image of the interaction (Fig. (b)).

NEUT and GENIE, have significant discrepancies in the low proton momentum region (Fig. 1) [4], where a gas HPTPC is capable of providing a momentum measurement. Improving the nuclear models with new data can already benefit currently running experiments.

First we describe the working principle of our HPTPC (Sec. 2) followed by the description of the actual prototype (Sec. 3). Section 4 covers the the HPTPC beam-test at CERN's PS accelerator. Finally, we summarise the analysis status of the beam test data and lay out the future steps (Sec. 5).

2 Working principle of an HPTPC with optical readout

The working principle of our HPTPC prototype with optical readout is described in Fig. 2. The track coordinates in the plane perpendicular to the drift field (xy-plane) are obtained with cameras, which are focused on the readout plane. The three meshes are not segmented, however the charge signal induced from the avalanches is read out. This information will be used to obtain information on the z-direction (parallel to E). Using appropriate optics and cameras a sub-mm segmentation can be achieved, where every segment is imaged by one camera pixel.

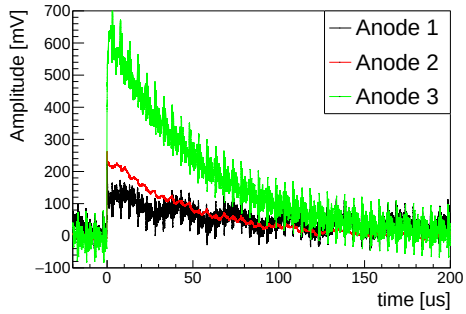


Figure 3: Simultaneous recorded anode signals during the calibration data taking

3 The High Pressure TPC prototype

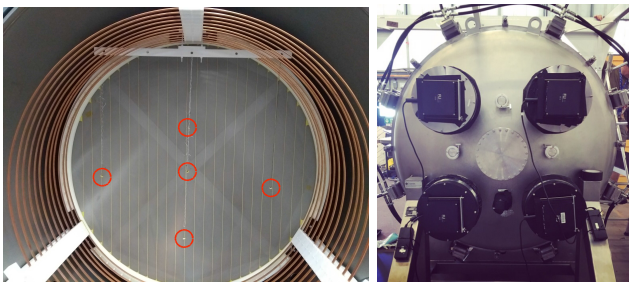
The HPTPC prototype follows the layout sketched in Fig. 2a: Four meshes with 1.2 m diameter are used for the cathode and the anode meshes. The length of the drift region enclosed by the cathode and anode 1 mesh is 44.7 cm. A field cage with 12 field-shaping strips encloses the drift volume and provides a uniform field. The distance between anode 1 and anode 2 (anode 2 and anode 3, respectively) mesh is 0.5 mm (1 mm, respectively). A CAEN NDT1470 multi-channel power supply provides the anode meshes with positive High Voltage (HV), while a Spellman SL 30 supply is used for the cathode. This supply can provide up to 30 kV, allowing to set a maximal electric field in excess of 600 V cm^{-1}. The potentials on the field strips are set with a voltage divider chain with 3 MΩ resistors, which is in contact with the cathode and degrades the negative cathode potential. A last resistor can be chosen according to the desired potential on the field strip closest to the anode. Figure 4a shows a view into the drift volume, while the pressure vessel is open.

Charge signals are read out from the three anode meshes using a decoupling capacitor of 10 nF and amplified with CREMAT CR-113 preamplifiers (Fig. 3). Afterwards they are digitised by a CAEN N6730 500 MHz digitizer with eight channels. The channels not used for the anode signals can be used to digitise signals from other systems.

The TPC is embedded in a pressure vessel allowing gas pressures of up to 5 bar gauge pressure. To change the gas mixture the vessel is evacuated to a pressure below 5×10^{-6} bar absolute pressure and then filled with the target gas mixture to the desired pressure.

3.1 Optical readout

Four optical flanges with quartz windows are mounted onto the vessel and on each a FLI Proline PL09000 CCD camera is installed (Fig. 4b). Each camera is



(a) (b)

Figure 4: (a) The inside of the pressure vessel with the TPC. The line of view is through the high-transparency cathode mesh along the drift direction towards the anode meshes. Red circles mark the ^{241}Am calibration sources. On the circumference the field cage rings are visible. (b) Same view on the closed vessel. The four CCD cameras mounted on the optical feed-throughs can be seen.

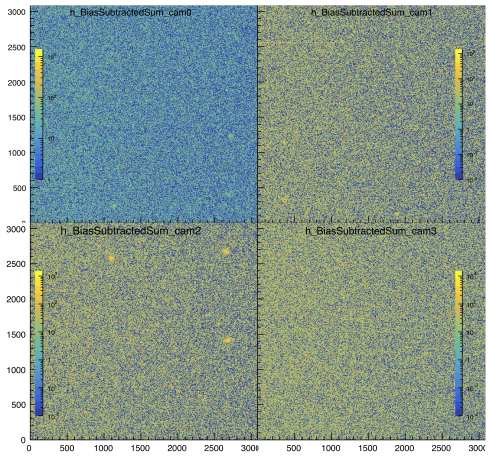


Figure 5: Light yield from the calibration sources (*cf.* Fig. 4a) for 200 s exposure time in pure Argon at 3 bar absolute pressure. The average pixel values of the top left camera picture differ from the other three camera pictures, because the corresponding camera has a different conversion gain compared to the other three cameras.

centred on one quadrant of the amplification region and focused there using a Nikon f/1.2 50 mm focal length lens. In the amplification plane the cameras provide a granularity of 3056 × 3056 pixel (pixel length of 230 µm) and they thus image a total area of 71 × 71 cm^2 each. In order to image a *e.g.* 2D projection of a particle's tracks, the electron amplification factor of the gas amplification stage (gas gain) has to be higher than the light attenuation factor of $\sim 10^{-4}$, which is caused by the different elements in the optical path.

A water cooling system is attached to each camera, lowering their temperature below the ambient temperature, so that the internal Peltier cooler cooling can reach 30 °C below the ambient temperature.

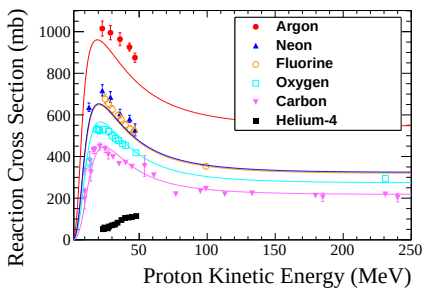


Figure 6: Existing data for proton-nucleus interactions at low proton momentum [5].

3.2 Calibration sources

Five low activity ^{241}Am sources are mounted inside the TPC (Fig. 4a) such that each camera can see three of these sources. They are used to assess the light gain of the amplification stage, since the ^{241}Am alpha particles with about 5.5 MeV energy produce enough primary ionisations to be visible even for moderate gas gain (Fig. 5).

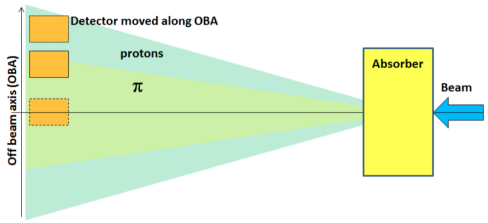
3.3 Detector control system

The detector is operated with a custom made slow control. This system controls the high voltage supply, the data acquisition system, and the gas supply system. All relevant parameters are logged together with other monitoring values as *e.g.* the gas temperature. While the camera shutters are open the digitiser accepts triggers from the three anodes or other, optional, signals. Each HPTPC event thus consists of four simultaneous camera exposures and all the waveforms recorded during the exposure time. The waveform acquisition triggers are freely configurable and usually a trigger on either anode signal is used.

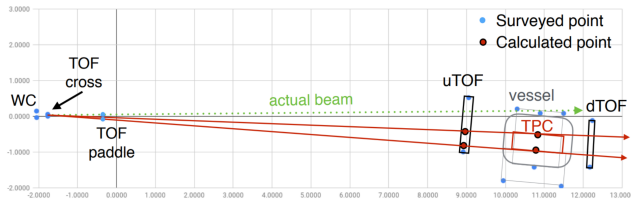
4 Beam test at CERN PS

The HPTPC has been tested for one month at CERN's PS accelerator with low momentum hadrons. Two goals have been defined beforehand: I) To access the general performance of the prototype in a particle beam, and II) To provide new proton-Ar nucleus cross-section measurement at low proton momentum. Figure 6 shows the currently available data, which only ranges up to 50 MeV/c. Adding new measurements will benefit the Neutrino Monte Carlo generators as discussed in Sec. 1 and Fig. 1.

In a measuring campaign before the actual beam time it has been established that the proton-to-pion ratio for a low momentum hadron beam ($\leq$ 0.4 GeV/c) in the T10 experimental area is not sufficient for our test program [5]. To reach momenta lower than 0.5 GeV/c while achieving at the same time a sufficient proton-to-pion ratio, the off-axis technique explained in Fig. 7a has been used. The TPC's active area is displaced by 3.5 ° with respect to the beam axis. After a 35 cm plastic absorber the first detector of the Time of Flight (TOF) system has been placed, followed by two TOF



(a)



(b)

Figure 7: (a) Off-axis technique: A hadron beam (protons and pions at 0.8 GeV/c) impinges on a plastic moderator. The scattered protons have a larger opening angle as compared to the scattered pions. Therefore placing the TPC off the beam axis allows to enhance the proton-to-pion ratio. (b) Placement of the different detector systems in the T10 experimental area at CERN's PS.

units on each side of the HPTPC (Fig. 7b). One of the TOF units uses SiPMs coupled to the scintillator bars instead of PMTs [6]. We are currently preparing a publication detailing the off-axis method and results of the TOF systems [7]. This will include results on a beam energy scan, studies with different absorber lengths as well as on-axis and off-axis measurements.

The HPTPC has been operated at different absolute pressures from 1 bar to 5 bar and different gas mixtures with Argon predominance: Pure Ar, Ar-CF_4, Ar-CO_2, Ar-N_2 and Ar-CO_2-N_2. The total quencher content was always kept in the 0.5 % to 3 % range. A high pressure gas monitoring chamber [8] has been employed to access the quality of the TPC gas.

The camera shutter opening was set to trigger on the *spill imminent* signal provided by the accelerator. The cameras took one exposure for each beam spill and several charge signals have been recorded during the exposure times. For calibration purposes the TPC has been furthermore operated without beam as well as without HV to check for beam interactions within the cameras' silicon.

4.1 HPTPC performance

The standalone analysis of the HPTPC data as well as the combined analysis of the HPTPC and TOF data is currently ongoing. We observe some tracks during the beam test in the raw-CCD data, using the on-line monitoring tool (Fig. 8). Most of these tracks have a length on the order of a cm or less. Given that the maximal diffusion over the whole drift length can amount to several mm, we assume that the tracks seen by eye originated close to the amplification region. A thorough analysis with a high level tracking algorithm will

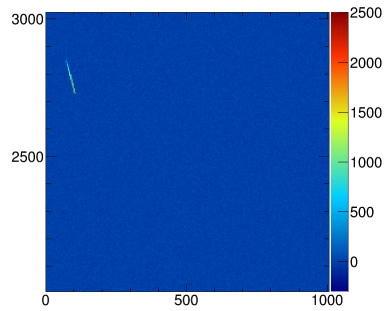


Figure 8: Example for a track in the HPTPC, visible by eye in the raw data without pedestal correction. Note the zoomed horizontal axis. The colour encodes the brightness of the signal.

identify tracks with higher diffusion, which are not visible by eye.

During the beam test the maximal gas gain was limited by anode sparking. We reassembled the detector after the beam-test at its host institution and could achieve higher gains. It is likely that some contaminant reached the amplification region during the HPTPC assembly at CERN, which then affected the operation in the beam.

5 Analysis status and outlook

After the beam-test and reassembly of the HPTPC in the United Kingdom an extensive calibration campaign at the CERN HV settings has been performed, using radioactive sources. Currently, the tracking algorithm is finalised and the analysis of the HPTPC data is integrated with the TOF data, using the custom analysis framework RAPTORR (Response in Argon to Protons at pressures of 3750 torr). This includes a cluster finding algorithm, allowing to identification of tracks with large diffusion. Subsequently, we will attempt to determine the specific energy loss ($d\varepsilon/dx$) of the measured tracks and calculate the proton-Argon cross-section.

In parallel, the analysis of the light yield and gas gain measurements are being completed.

Our large data set of calibration- and beam-data will then be used to tune the detector Monte Carlo simulations for high pressure gas detectors. We continue to further develop the detector and coordinate wider HPTPC R&D efforts. This will include exploring Micro Pattern Gaseous Detector technologies for the amplification stage in order to provide a higher gas gain, and in turn, light gain, which will facilitate the optical readout.

The cross-section measurement will hopefully prove to be a valuable input for calculation of FSI in neutrino-Argon scattering.

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