The status and results from ProtoDUNE Single Phase

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Abstract. DUNE is a leading-edge, international experiment for neutrino science and proton decay. Its ambitious physics program requires a careful prototyping of the engineering solutions envisaged for the scale-up of the LArTPC technology, as well as a careful control of the systematics through the acquisition of a deep knowledge of the detector response and performances. ProtoDUNE is an an extensive prototype program developed at the European Research Center (CERN) Neutrino Platform facility with the aim to answer to all the open questions about DUNE design. The Single Phase prototype (ProtoDUNE SP) has been assembled between 2017 and 2018 and it successfully took its first beam data from a dedicated SPS tertiary line from September to November 2018.

1. Introduction
The Deep Underground Neutrino Experiment (DUNE) is an international long-baseline experiment for neutrino science and proton decay studies [1]. DUNE will build an intense neutrino beam from Fermi National Accelerator Laboratory in Batavia (Illinois) to a far detector, consisting of four Liquid Argon Time Projection Chambers (LAr-TPC) holding in total around 68 ktons, at the Sanford Underground Research Laboratory in South Dakota at 1300 kilometers downstream of the source. The availability of two variants of the LAr-TPC technology, Single-Phase and Dual-Phase, for the DUNE far detector has led to an extensive prototype program (ProtoDUNE) development at the European Research Center (CERN) Neutrino Platform facility.

2. ProtoDUNE-SP Detector
With its 720 tons of liquid argon (411 active volume) ProtoDUNE Single Phase is currently the largest existing LAr-TPC and has the longest drift distance between cathode and anode planes. The aim of the ProtoDUNE program [2] is to better define the production and installation procedures for DUNE FD as well as accumulate test-beam data at CERN in order to calibrate the response of the detector to different particles species.

The detector is located in an extension to the EHN1 hall at CERN and it took its first beam-data from the H4-VLE tertiary beam line before the LHC long shutdown at the end of 2018. The SP TPC detector (figure 1) consists of 6 full-size Anode Plane Assemblies (APAs) for a total of 15,360 TPC sense wire and electronics channels. The 500 V/cm electric field is produced by the 3 Cathode Plane Assemblies (CPA) installed in the inner part of the TPC for a total of 2 x 3.6 m drift regions. The 16 field cage aluminium profiles allow to maintain a uniform...
Figure 1. ProtoDUNE SP LAr-TPC schematic design.

electric field between the cathode and anode. The top and bottom of the TPC are equipped with perforated stainless steel ground planes to ensure no field outside the active volume. The photon detection system is integrated in the APAs. Electric charge signals from the APAs are digitised in the Cold Electronics along the top of each APA. Power, signal and data connections to the outside are done with cables running through one dedicated feedthrough on the cryostat roof for each APA.

2.1. Cold Electronics Read out

According to physics simulations, the Equivalent Noise Charge (ENC) of DUNE SP far detector should be less than 1/9 of the expected worst case (instantaneous charge arriving at the APA from a MIP) which requires ENC for induction wires to be less than $1000 \, e^-$. To this purpose, a readout electronics integrated with detector electrodes has been developed by BNL for cryogenic temperatures ($77 - 89 \, K$). In this configuration, the noise is independent to the fiducial volume and much lower than with readout electronics at room temperature [3]. It consists of 20 Front-End Mother Boards (FEMB) installed close to the wire electrodes on top of each APA (120 FEMB in total). The FEMB purpose is to amplify, shape, digitize and transmit 15,360 TPC channels to the warm interface electronics through cold data cables. The warm electronics is the interface between the cold electronics and the DAQ system. It is housed in the Warm Interface Electronics Crates (WIECs) attached directly to the signal feed-through flanges. Each WIEC has one Power and Timing Card (PTC), five Warm Interface Boards (WIBs) and a passive Power and Timing Backplane (PTB) inside the crate. The PTC provides a bidirectional fiber optical link to the timing system. It is used to fan out clock and control signals to WIBs through the PTB. A WIB, which hosts 4 FEMBs, forwards system timing signals to FEMBs and receives the high-speed data from FEMBs simultaneously. WIBs also reorganizes and transmits the data to the DAQ system over fiber optical links. The cold electronics performance can be studied using the integrated local diagnostic on WIB without DAQ system, which was a crucial
tool during the cold electronics installation and checkout tests.

2.2. PhotoDetection system
The Photon Detectors (PD) are acrylic light-guide bars running across the middle of each APA and read out on one side by SiPMs. Two variants of photodetectors have been used. In the first variant, the light-guide bar contains Y-11 WLS fluor and it's surrounded by thin plates coated with TPB which shifts the 128nm Argon scintillation light to 430nm. The second variant is just dip-coated with TPB. Each APA carries 10 PD bars equally split between the two variants. Additionally, two APAs carry one module each of further different design, the ARAPUCA, where scintillation light is shifted, trapped and collected in square volumes along each bar. Analogue signal cables from all PD SiPMs are routed through the APA vertical frames and out of the cryostat through purpose-made feedthroughs, to custom-built readout cards (SSP) connected to the DAQ through optical fibres.

2.3. Cathode Plane Assemblies (CPA)
The ProtoDUNE-SP CPA is made of 6 columns, each one made of 3 modules. To avoid damage to the TPC, including the electronics, in case of discharges, CERN and BNL developed and constructed an all-resistive cathode made of Dupont Kapton resistive film laminated on FR4. The FR4 structural elements also tie the plates together.

2.4. HV and Field Cage
To achieve a 500 V/cm electric field throughout its drift area, the ProtoDUNE-SP cathode must be held at -180 kV. An intense range of HV tests have been performed both at CERN and Fermilab in order to validate design and material choices. The Field Cage is made of extruded, open Aluminium profiles supported by fiberglass beams. Each module has its own resistor chain and is isolated from the adjacent modules, again to minimise the energy dump in case of sparks. Perforated stainless steel ground plates surround the top and bottom FCs to protect the TPC from discharges to the membrane or objects (pipes, instrumentation) between FC and the membrane. Two vertical units at its upstream and downstream ends complete the enclosure around each volume.

3. TPC installation and commissioning
In August 2017, the production of all components was underway and integration at CERN [4] was starting with the first APA. Once delivered at CERN, each APA has been lifted out of its delivery box, rotated in vertical position and moved inside the NP04 clean room. Once in the clean room, it was visually checked before going on with the first wire tension check. Tension of sample wires has been measured by plucking them and recording their resonant frequency by using a laser pickup. The same check on sample wires has been repeated after the Cold Box integration test [5].

Second step was the PD installation. After reception, PD assemblies has been tested into the Clean Room in a purpose-made dark box with LED light pulsed along their length, then installed on the APA and their cables routed through its frame. Lastly, the complete system was checked out for bad channels and any necessary repairs were made. Finally, PD cables were bundled and secured on their cable tray on top of the APA.

Cold Electronics was the last phase of APA integration. Once delivered, a first reception test has been performed at room temperature on FEMBs in order to verify the response and functionality of all readout channels. The same test was repeated on each FEMB after the installation on the APA and for each FEMB bunch (4 FEMB to be connected to the same WIB) after the cabling on top of the APA.
Figure 2. ProtoDUNE TPC from the inside after commissioning was completed. From left to right, it is possible to observe in their final position 3 APAs, filed cage profilers and CPA modules.

In order to evaluate full-size APA performance at cryogenic temperature, a Cold Box was built for integration test [5]. The integration test included a full-size signal feed-through assembly and used cables and readout electronics identical to the production system. This allowed vertical slice test of all the APA components at the same time (wires, electronics and photon detectors) and to replace those components failing at cold temperatures before the APA insertion inside the cryostat.

At the same time, CPA modules were also assembled inside the clean room and moved into the cryostat. Field cage profiles were also assembled together with the CPA modules at this stage and fixed in their final position during the commissioning.

In April 2018, all TPC components were installed inside the cryostat. From this moment, an intense series of commissioning activities started in order to be ready for the first data beam run on September 2018. Commissioning included fixing the APAs and field cage end walls in their final position, installation of the high voltage cup and feedthrough and the installation of all the cryo-instrumentation, cameras, LEDs, purity monitors and temperature sensors. In figure 2, an internal view of one TPC drift region after commissioning is shown.

3.1. H4-VLE beam line
In the meantime, the new H4-VLE beam line has been assembled by CERN EN-EA group with the joint of ProtoDUNE Beam Instrumentation group. The H4-VLE beam line comes from an extension of the secondary 80GeV/c pions beam line, coming in turn from a first extension of the 400GeV/c primary beam from SPS. It consists of tertiary $e^-, p, \mu^+, \pi^+$ beam with energy range from a 0.5 to 7 GeV/c The beam line elements are showed in figure 3.
3.2. Cosmic Ray Tagger
During the detector commissioning, a Cosmic Ray Tagger system has been installed on the two sides of the detector along the beam line. The CRT system is made of 1.6 x 3.2 m active size modules made of two layers each of 5 cm-wide scintillator bars. The scintillator bars are read out with PMTs through optical fibres mirrored on one end. The integration of CRT in the DAQ and data analysis systems allowed to tag cosmic and beam halo muons traversing the TPC at very shallow angles and it has been a crucial tool for understanding, calibrating or correcting for detector effects.

3.3. Data Acquisition System
A parallel activity to the TPC installation was the development of the DAQ system. A schematic design of DAQ is shown in figure 4. The TPC readout (both RCE and FELIX) accepts data from the TPC Warm Electronics at total rate of 480 Gb/s, where it is compressed and selected based on trigger information. Triggered data is then sent to the artDAQ event builder farm, and subsequently stored to disk with a parallel sample sent for online monitoring. Triggers are formed from inputs coming from several system, namely the beam instrumentation, photon detection and cosmic ray tagger, and forwarded to the timing system which broadcasts the synchronous trigger and clock signals to the electronics and DAQ systems.

4. ProtoDUNE beam run
In July 2018, the commissioning activities had been completed and the purging and filling operations started. By mid September 2018, the detector was fully filled with LAr and ready for the activation process. On September 21, 2018, the HV on cathode achieved for the first time its nominal value of 180kV. This was a real challenging goal for the ProtoDUNE HV group and its achievement was the first great success of the experiment.
At that time, the argon purity was not enough to visualize beam tracks. However, it was still possible to observe first detector tracks close to APA wires coming from cosmic rays (figure 5). In the following days, cosmic tracks further into the drift region were recorded, confirming the increasing of the argon purity.
On October 2, 2018, the first beam track has been observed (figure 6).
4.1. Beam-run summary
ProtoDUNE SP took data from the tertiary beam line from September 21 to November 12, 2018. During this period, beam run time was alternated to weeks without beam, dedicated to both cosmic data taking and detector maintenance activities. In figure 7 a summary of the estimated (from beam simulation) amount of pion, proton, positron and kaon events collected at each momentum during the beam run. The amount of collected data was more than the expected from schedule, especially in the $< 1GeV$ region where DUNE will be more sensitive. The reached purity was another great success for ProtoDUNE SP, reaching a maximum of more than 6 ms electron lifetime (figure 8).

5. Conclusions
The ProtoDUNE-SP project at CERN has been an incredible challenge with a real successful result. The beam and cosmic data collected by the detectors will be extremely important to address and define the systematic uncertainties of DUNE measurements.
Figure 6. First data ray track observed from ProtoDUNE SP on the offline event display on October 2, 2018.

| Momentum | Total Triggers | Expected Pi trig. | Expected Proton trig. | Expected Electr. trig. | Expected Kaon trig. |
|----------|----------------|-------------------|----------------------|-----------------------|-------------------|
| 0.3 GeV/c| 269K           | 0                 | 0                    | 242K                  | 0                 |
| 0.5 GeV/c| 340K           | 1.5K              | 1.5K                 | 296K                  | 0                 |
| 1 GeV/c  | 1089K          | 382K              | 430K                 | 263K                  | 0                 |
| 2 GeV/c  | 728K           | 333K              | 128K                 | 173K                  | 5K                |
| 3 GeV/c  | 568K           | 284K              | 107K                 | 113K                  | 15K               |
| 6 GeV/c  | 702K           | 394K              | 70K                  | 197K                  | 28K               |
| 7 GeV/c  | 477K           | 209K              | 51K                  | 98K                   | 20K               |
| All momenta | 4175K         | 1694K             | 779K                 | 1384K                 | 73K               |

Figure 7. Summary of the estimated (from beam simulation) amount of pion, proton, positron and kaon events collected at each momentum during the ProtoDUNE SP beam run.

The detector will take cosmic rays data all over 2019 in order to investigate on few important detector improvements as the HV system stability and the argon purity as well as software improvement on DAQ system and analysis.
Figure 8. Electron lifetime trend during the beam run of ProtoDUNE SP.

References

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