ProtoDUNE Detector

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The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021)

September 9, 2021
• DUNE: next generation neutrino experiment using LArTPC technology
  - New neutrino beam at Fermilab (1.2 MW, upgradable to 2.4 MW), 1300 km baseline
  - 4 modules for Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
  - Multiple technologies for the Near Detector (ND)
• $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance $\rightarrow$ Neutrino CP violating phase and mass ordering
• Large detector, deep underground, high intensity beam $\rightarrow$ Supernova burst neutrinos, atmospheric neutrinos, nucleon decay and other BSM, etc
• Excavation started in 2017, start Far Detector installation in the middle of 2020s
ProtoDUNE at CERN

- ProtoDUNE-SP and DP are DUNE’s large scale prototypes (~1 kton-scale) of its far detector modules at CERN Neutrino Platform
  - Use components identical in size to those of the full-scale module
  - Critical to demonstrate viability of LArTPC technology

ProtoDUNE Dual Phase (DP)
- LArTPC 6 m vertical drift + charge amplification in gas Ar + photon detection
- Cosmic-muon data in 2019 - 2020

ProtoDUNE Single Phase (SP)
- LArTPC 3.6 m horizontal drift + photon detection
- Beam data taken in 2018 & cosmic data in 2018 - 2020
- ProtoDUNE-SP Phase II in 2022
ProtoDUNE-SP: Operating Principle

- Charged particles ionize argon atoms
- Ionized electrons drift horizontally opposite to the E field in the LAr and are collected on the anode wire planes (∼ ms) → 2D spatial location
- Electron drift time projection → enable 3D spatial location
- Argon scintillation light (∼ ns) detected by photon detectors, providing event start time $t_0$
- Key factors: LAr purity and noise on the readout electronics
ProtoDUNE-SP at CERN Neutrino Platform

- Tertiary beam
- Spectrometer to measure the particle momenta
- Particle ID from time of flight and two Cerenkov detectors
- Over 4 million triggers over the momentum range 0.3 to 7.0 GeV (positrons, pions, muon, kaons and protons)

**Journal of Instrumentation**  
B. Abi *et al* 2020 *JINST* 15 P12004

**OPEN ACCESS**
First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform
Published 3 December 2020 • © 2020 CERN  
*Journal of Instrumentation, Volume 15, December 2020*  
*Citation B. Abi *et al* 2020 *JINST* 15 P12004*
ProtoDUNE-SP Detector

- **TPC**
  - Two drift volumes, 3.6 m drift distance (2.25 ms) @ 500 V/cm
  - Cathode Plane Assembly (CPA) on middle plane
  - Anode Plane Assemblies (APAs) on both sides
  - Cold electronics attached to the top of APAs

- **Photon detectors (PDS)**
  - SiPM readouts
  - Wavelength shifter converts VUV to visible light
  - 3 designs integrated into APA frame bars

- **Cryogenic instrumentations**: measure argon purity, temperature, liquid level and tag cosmic rays
Event Displays in ProtoDUNE-SP Data

- Cosmic Rays
- 1 GeV Stopping Proton
- 6 GeV Pion
- 6 GeV Electron
The APA

- APA: 3 wire planes (U/V, X) + 1 grid plane (G)
  - Grid plane prevents induction currents from drifting charge in drift volume
  - Induction wires (U, V): inclined at ±35.7°, transparent to charges
  - Collection wires (X): collect charge forming unipolar signal
  - Grounding Mesh helps to shape an uniform electric field near the collection plane
The Photon Detection System (PDS)

- LAr is highly transparent to its scintillated light: 24,000 photons/MeV @ 500 V/cm, wavelength=128 nm
- 3 technologies based on light-guide modules with wavelength shifter (WLS) read by arrays of 3 or 12 SiPM
- Detailed study of the performances for the 3 designs and the various SiPM configurations to define the layout for DUNE
The Photon Detection System (PDS)

- **Dip-coated light guide:**
  - 128 nm → 430 nm
  - Acrylic light guide bar dip-coated with wavelength shifter
  - Transport shifted light via total internal reflection to the readout on one side

- **Double-shift light guide**
  - 128 nm → 430 nm → 490 nm
  - Wavelength-shifting plates + wavelength-shifting light guide
  - Transport shifted light via total internal reflection to the readout on one side

- **Arapuca**
  - 128 nm → 360 nm → 420 nm
  - First shift from a dichroic optical filter, second shift on the bottom
  - Photons non directly absorbed are trapped and reflected till they hit one SiPMs, 5~10x light yield increase
ProtonDUNE-SP: View from Inside

One of the two TPC volumes

Field cage
Photon detectors
APAs
Cathode
ProtoDUNE-SP TPC Performance: LAr Purity

- Liquid Argon purity is routinely measured by three Purity Monitors
- High purity reached thanks to the gas/liquid recirculation & filtering
  - Lower limit of 30 ms lifetime over the majority of run period → 7% signal reduction over the entire 3.6 m drift distance (2.25 ms drift time)

\[ \frac{Q_A}{Q_C} = e^{-t_{\text{drift}}/\tau} \]
ProtoDUNE-SP TPC Performance: Det. Stability

- TPC signal strength: The average charge per channel from cosmosics
  - A monitor of overall detector response
  - Sensitive to amplifier/digitizer response, cathode voltage, LAr purity and other detector conditions
- Response has been stable over the 22 months of operation
ProtoDUNE-DP: Operating Principle

- Ionized electrons drift vertically upward in LAr
- Electrons are extracted from liquid into gas phase above the liquid
- Charge signal amplified and read out at the top
- PMTs detect scintillation light at the bottom
- Challenge: the overall design increases the possible drift length which requires a correspondingly higher voltage
ProtoDUNE-DP Detector

- **Induction Field**: nominal at 5 kV/cm
- **Amplification Field**: nominal at 30 kV/cm
- **Extraction Field**: nominal at 2 kV/cm in LAr
- **Drift Field**: nominal at 0.5 kV/cm

**Components:**
- Charge Readout Planes (CRP)
- Field Cage
- Cathode (300 kV)
- Ground grid
- Photomultipliers

**Dimensions:**
- 6 m length
- 6 m height
- 6 m width
ProtoDUNE-DP: Cosmic Ray Events

- Events with LEM $\Delta V$ of 31–32 kV (Oct. 2019)

- Horizontal muon track

- Electromagnetic shower + 2 muon decays

- Multiple hadronic interactions in a shower
Summary and Prospect

• The successful performance of ProtoDUNE-SP LArTPC using large samples of data from a test-beam run at the CERN Neutrino Platform demonstrates the effectiveness of the single-phase detector design and the execution of the fabrication, assembly, installation, commissioning, and operation
  - The data collected by ProtoDUNE-SP during beam runs and cosmic-ray runs will allow more detailed studies of detector characteristics and the measurement of argon-hadron cross sections
  - ProtoDUNE-SP Phase II, to test the final design for DUNE, is expected to start in late 2022

• ProtoDUNE-DP is the largest dual-phase TPC ever built and operated
  - Plenty of data to be analyzed and many interesting results to be share with a wider community interested in large LAr TPCs

Stay tuned!
Backup
ProtoDUNE-SP TPC Data Preparation

- Careful TPC data pre-processing and calibration to extract the ionizing signal
  - Data preparation: Pedestal subtraction, noisy/bad channel flagging, timing mitigation, tail removal, correlated noise removal
  - Charge calibration: using known pulse with variable amplitude

Example event displays for a collection plane showing background reduction in successive stages of data processing
ProtoDUNE-SP: Electronic Noise and S/N Ratios

- Electronic noise level measured by pedestal ENC (equivalent noise charge) before noise filtering: Collection (X): 550 e-, Induction: 650 e- (DUNE goal < 1000 e-)

- Noise filter reduces both by ~ 100 e-

- Noise-filtered signal-to-noise ratio measured by cosmic muons: Collection: 48.7:1, Induction: 21.2:1
  - Far better than the nominal design value (S/N=9)
ProtoDUNE-SP: Event Reconstruction

- From the deconvolved waveforms to fully reconstructed interactions
  - Hit finding: gaussian fit of waveform peak
  - Pattern recognition with Pandora: from 2D to 3D hit clustering, 3D detector slicing, determination of cosmic/beam data, particle hierarchy
ProtoDUNE-SP: Detector Calibration

- Individual effects are measured and corrected for:
  - SCE (Space charge effect), attenuation, electronic gain, diffusion, recombination, etc
  - Detector response is uniform in space and over time after the corrections
- Absolute energy scale is determined using stopping muons
ProtoDUNE-SP: dE/dx Measurements

- The calibration constants applied to test beam particles and yielded good data and MC agreements
  - Excellent $\mu^+/p$ separation: crucial for cross section measurements
  - Good $e/\gamma$ separation: crucial for DUNE’s neutrino oscillation measurements

Precise dE/dx leads to excellent $\mu^+/p$ separation

Good $e/\gamma$ separation crucial for electron neutrino ID
SP: Beam electron energy reconstruction

- Electron energy resolution is crucial for DUNE’s oscillation measurements
  \[ E_{\nu_e} = E_e + E_{\text{had}} \]
- Two analyses to measure beam electron energy resolution
  - TPC charge information
  - Photon detector information with only one ARAPUCA bar
SP: Beam electron energy resolution

\[ \sigma_E / \langle E \rangle = \sqrt{a^2 + (b/\sqrt{E})^2 + (c/\langle E \rangle)^2} \]

- Good linearity seen in both analyses
- Constant term dominated by spread of beam momenta
- Noise term dominated by fluctuation in the energy loss upstream
- Stochastic term characterizes the intrinsic detector resolution
  - \(~ 2\%\) for TPC and \(~9.9\%\) for PD
  - Better than the design requirements
SP: Photon Detector Performance

- Good energy linearity for contained beam electrons in the detector
- Working on geometry, attenuation and efficiency corrections
DP: Operating Principle

- Homogeneous 0.5 kV/cm drift field (cathode + field cage)
- Extraction field ~ 2.5 kV/cm between grid and LEM bottom
- Amplification ~ 20 in LEMs holes
- Readout in two directions (3.125 mm pitch) by collection on anode via field between LEM top electrode and anode
DP: Charge Readout Plane gain measurement

- Measurements between Sept. 2019 and Jan. 2020 with cosmics
- Operating conditions: 1045 mbar and ~ 90 K
- CRP gain: $\epsilon_{\text{extraction}} \times \epsilon_{\text{LEMs,amplification}} \times \epsilon_{\text{Qcollection}}(E_{\text{induction}})$
- $\epsilon_{\text{extraction}}$ estimated to be well above 90%

- Sept. $\rightarrow$ Nov: Reduction by at least a factor of 2 due to LEM charging up effects
- Nov. $\rightarrow$ Jan.: very small reduction, charging up completed
- Gain a factor of 2 lower than extrapolated from previous prototypes
- Discrepancy not yet understood, dedicated study to come