ProtoDUNE Dual Phase

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Deep Underground Neutrino Experiment

- Leading-edge, international experiment for long-baseline neutrino oscillation studies, and for neutrino astrophysics and proton decay searches
- DUNE aims at answering fundamental questions related to:
  - the matter-antimatter asymmetry (neutrino oscillations and mass ordering)
  - the Grand Unification of forces (proton decay searches)
  - the supernova explosion mechanism (supernova neutrino detection)

DUNE Far Detector

4 10-kt (fiducial) LAr TPC modules:

- Underground: at 1480 m depth
- Size ~ 12x12x60 m³
- “2 +1 +1” model:
  - 2 SP FD module (first one will be SP)
  - 1 DP FD module
  - 1 “opportunity” FD module

Single Phase

Dual Phase
DUNE collaboration & timeline

Over 1000 collaborators from 175 institutions in 32 countries

2018/19 - ProtoDUNEes @ CERN
2019 - Technical Design Report
2019 - Far site primary excavation begins
2022 - First FD module installation begins
2026 - Neutrino beam and near detector available

First data expected in 2024!
LAr TPC technology

- Liquid Argon Time Projection Chamber: 3D reconstruction and particle identification
- Two technologies: single phase (w/o amplification) and dual phase (w/ amplification)

SINGLE PHASE

DUAL PHASE

* Next talk by Pablo Fernández (ProtoDUNE-SP)
LAr TPC technology

- **Liquid Argon Time Projection Chamber:** 3D reconstruction and particle identification
- **Two technologies:** single phase (w/o amplification) and dual phase (w/ amplification)

### Dual Phase

- **Charge from ionization:** for tracking and calorimetry
- **Scintillation light:**
  - S1 [fast & slow] in the liquid (*trigger and t₀*)
  - S2 in the gas (*additional charge information*)

*The charge and light goals are the same for the SP (w/o S2)*

- **DP advantages w.r.t. SP**
- **DUNE DP FD drift:** 12 m! Real challenge…
ProtoDUNE@CERN

NP02: ProtoDUNE-DP

NP04: ProtoDUNE-SP

EHN1 Facility
3x1x1 m³ prototype

- 4.2t DP LAr TPC: largest DP operated so far!
- It took cosmic muon data in 2017 at CERN
- Tech. paper accepted by JINST (arXiv:1806.03317v2)

Design of ProtoDUNE-DP validated!

Different configurations for PMTs tested: TPB coating, HV divider…
3x1x1 m³ prototype

The light physics in WA105


- Study of the S1: LAr purity, $\tau_{\text{slow}}$ vs time, vs drift field...
- Study of the S2: drift time, S1/S2 vs amplification field...
- Light-charge correlation
- Data-MC comparison: good agreement so far and more improvements are expected soon
ProtoDUNE-DP (6x6x6 m³)

- 300t DP LAr TPC: scalable to DUNE!
- It will take cosmic muon data in 2019

Charge extraction, amplification and readout

- Induction: 5 kV/cm
- Amplification: 33 kV/cm
- Extraction: 3 kV/cm (GAr)
- Extraction: 2 kV/cm (LAr)
- Drift: 0.5 kV/cm

Scintillation light detection
(S1 & S2 signals)

TDR: arXiv:1409.4405
CURRENT STATUS AND PLANS

- **Field cage complete**: April 2018
- **Successful test at 150 kV** on field cage!
- **Light detection system is ready** for being installed
- Modifications on the **HV LEM distribution** are ongoing
- **Cold box tests** of the CRPs: crucial to upgrade and validate the final design
- Assembly of the CRPs is almost finished and **installation is foreseen for November 2018**
- Installation of the **rest of the components** (cathode, ground grid, PMTs…) will require at least **5 more weeks**

**NP02 cryostat will be closed in January 2019!**
ProtoDUNE-DP Light Detection System

GOALS OF THE LDS:
* Validation of the system for DUNE
  ‣ Trigger for non-beam events
  ‣ $T_0$ for both beam and non-beam events (cosmic background rejection)
  ‣ Possibility to perform calorimetric measurements and particle identification

BASIC CONFIGURATION:
* 36 8” cryogenic photomultiplier tubes
* Wavelength-shifter: TPB coating on PMT
* Voltage divider base + single HV-signal cable + splitter (external)
* Light calibration system
* External DAQ system

TDR: arXiv:1409.4405
PMT characterization @ CIEMAT

- Study of the performance at cryogenic temperature of the 8” R5912-02mod cryogenic PMT of 14 dynodes from Hamamatsu
- Detailed characterization of 40 PMTs (36 +4 spare) at warm and cold

MEASUREMENTS:
- Dark current rate vs. HV (reject noisy PMTs)
- Gain vs. HV (optimum operating HV)
- Light linearity (linear operating range)
- Light rate (avoid PMT saturation)
- Time signal characterization

DEDICATED SETUP
- Cryogenic setup for 10 PMTs testing (300 L vessel)
- PMTs immersed in LN2 (77 K)
- Configurable amount of light
- Diffuser for a uniform illumination

* Results recently published:
PMT characterization @ CIEMAT

DARK CURRENT

- DC vs HV at RT and CT for the 40 PMTs
- DC at CT > DC at RT for the same gain
- DC rate at CT reasonable for a good operation: less than 2.5 kHz at G=10^7

GAIN

- G vs HV at RT and CT for the 40 PMTs
- HV for G=10^9 at RT compared to Hamamatsu values: good correlation
- 71±14 % of gain drop on average at CT (w.r.t G=10^7 at RT)
PMT characterization @ CIEMAT

GAIN & FATIGUE EFFECT

- Fatigue: gain reduction when the PMT output current increases
- Quantitative study carried out
- No fatigue effect observed at RT: much slower recovery at CT
- The time needed for a complete gain recovery depends on the PMT and on the maximum output current
- Examples after high...

... GAIN (~ $6 \cdot 10^8$)

$\Delta G \sim 30\%$

Recovery time ~ 10 h

... LIGHT INTENSITY (~ $10^3$ p.e.)

$\Delta G \sim 30\%$

Recovery time ~ 1 day

... LIGHT RATE (MHz)

$\Delta G \sim$ factor 0.5

Recovery time: days-weeks
PMT characterization @ CIEMAT

LIGHT LINEARITY

Goal: to define the dynamic range for a linear response in similar conditions to the ones of ProtoDUNE-DP

Dependency with pulse profile (anode saturation): LED (40 ns pulses) vs laser (<1 ns pulses)

At CT, linear up to ~ 300 p.e. at G=10^7

LIGHT RATE

Goal: to study the effect of the continuous background of light pulses from S2 expected in ProtoDUNE-DP

3 regions: linear range, over-linearity region and saturation region (base saturation)

PMT response linear up to ~ 1 MHz at CT: far enough
Light calibration system

- Dedicated system to determine the PMT gain and to monitor the stability of the PMT response
- **External system**: 6 LEDs + reference sensor (SiPM) + fiber
- **Internal system**: fiber + 1-to-7 fiber bundle (x6)
- External and internal components have been characterized (internal ones at RT and CT)
- Attenuation at CT from flange to PMTs:
  - Expected from individual characterization: $<19.1\pm0.4$ dB
  - Measured by PMTs: $20.4\pm0.9$ dB
- The complete fiber calibration system at CT has been validated with a good performance in dedicated PMT measurements
- Paper in preparation!
**TPB coating**

**Purpose:** to convert UV LAr scintillation at 128 nm to visible light where PMTs are sensitive

- Coating facility at CERN for ICARUS experiment (description of the system: arXiv:1807.07123v3)
- Photocathodes coated with >0.2 mg/cm² in the middle
- Maximum difference in thickness: <20% edge-middle & <5% middle-center
- Quantum efficiency measurements at 128 nm after coating are ongoing

TPB coating of the 40 PMTs completed in Summer 2018
Summary

ProtoDUNE Dual Phase Light Detection System tasks (IFAE-CIEMAT):
- Characterization of 40 PMTs: done ✓
- TPB coating of 40 PMTs: done ✓
- Light Calibration System design & validation: done ✓

Everything is ready for installation!

- DUNE is the next generation long-baseline neutrino experiment that aims at addressing key questions in neutrino physics and neutrino astrophysics.

- In order to validate the LAr TPC technology on the massive scale, several prototypes are being developed at CERN.

- The performance of the 3x1x1 m³ demonstrator (WA105) with cosmic muons was successful and the results have validated the protoDUNE-DP design.

- The installation of ProtoDUNE Dual Phase is ongoing and expected to be finished by January 2019.

- The Light Detection System of ProtoDUNE Dual Phase, formed by 36 PMTs, will add precise timing capabilities. It will include a dedicated fiber calibration system which has been already validated. 40 PMTs have been characterized at CIEMAT and coated with TPB at CERN. They are currently stored at CERN and ready for installation.

- ProtoDUNE Dual Phase is expected to take data with cosmic muons in 2019 and with a charged-particle beam in the next years.
Thank you!
Backup
LBNF Beam & near detector

THE BEAM

- High purity $\nu_\mu$ beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradeable to 2.4 MW
- Year 7 (2032): upgrade to 2.14 MW (80 GeV proton) beam

THE NEAR DETECTOR

- Primary purpose: to constrain systematic uncertainty for long-baseline oscillation analysis
- The ND design has not been decided yet
PMT BASE VALIDATION

Two possible configurations:

- **Positive base (PB):** 1 cable, HV+
- **Negative base (NB):** 2 cables, HV-

- PMTs with PB show better response with light intensity and light rate, and lower dark current rate.
Gain calibration curves

- To characterize the PMT gain (number of electrons recorded at the anode / photoelectron emitted from the photocathode), a small amount of photons is sent to the PMT
- **SPE spectrum fit (left):** convolution of a Poisson distribution (number of p.e. generated in the photocathode), and a binomial distribution (two amplification paths: through the 1st dynode and in the 2nd dynode)
- **Gain calibration curve (right):** fit follows the power law $G=AV^B$ where $A$, $B$ depend on number, structure and material of the dynodes

$$\begin{align*}
G & \text{ drop w.r.t. RT (G=10)} & \{ & \text{60±9\% (4 PMTs) -> 83K} \\
& & \text{71±14\% (40 PMTs) -> 77K} & 
\end{align*}$$