PROCEEDINGS OF SCIENCE

Overview and Status of the 2x2 ND-LAr Demonstrator: A Pixel-Based LArTPC Prototype for the DUNE Near Detector

K. Wresilo[a,*] **on behalf of the DUNE collaboration**

[a] *The Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, CB3 0HE, United Kingdom*

E-mail: kwresilo@hep.phy.cam.ac.uk

The Deep Underground Neutrino Experiment (DUNE) is a future long-baseline neutrino oscillation experiment featuring a 70 kt liquid argon (LAr) far detector. The near detector complex, situated at Fermilab, includes ND-LAr - a LAr detector that is critical for constraining systematic uncertainties via in situ measurements to enable precision studies of neutrino oscillations. Challenging event pile-up from the world's most intense 1.2 MW neutrino beam will be mitigated by a combination of a modularised detector design and state-of-the-art readout technologies. True 3D pixel-based charge readout capabilities combined with high-timing resolution light readout will eliminate ambiguities that would otherwise arise in conventional wire-based LAr detectors. This document describes the novel design of the detector and its subsystems, highlighting the key performance results from commissioning and the current status of the ND-LAr 2x2 Demonstrator, an ND-LAr prototype that has recorded the first neutrino data for the DUNE collaboration.

42nd International Conference on High Energy Physics (ICHEP 2024)
18th-24th July 2024
Prague, Czechia

*Speaker

PoS(ICHEP2024)176

1. The DUNE Experiment and the Role of the Near Detector

The Deep Underground Neutrino Experiment (DUNE) is a future-generation, long-baseline accelerator neutrino experiment currently under construction. It consists of a powerful beam that is upgradeable to 2.4 MW, a first-of-its-kind near-detector (ND) located at Fermilab, Illinois, and a 70 kt liquid argon (LAr) far-detector (FD) situated 1 mile underground and 800 miles downstream of the ND in Lead, South Dakota. With high-statistics data samples facilitated by the combination of an intense beam and kiloton-scale liquid argon time projection chamber (LArTPC) detectors, and tight control of systematic uncertainties through ND measurements, it aims to probe the 3-flavour neutrino framework delivering neutrino oscillation measurements with unprecedented precision. This includes unambiguously resolving the mass ordering with just 100 kt-MW-yr exposure, and a 5σ sensitivity to 50% of the allowed δ_{CP} values in 10 years [1] [2].

The ND complex is critical to meeting the allowed systematic uncertainty budget required for precision measurements. It consists of a suite of complementary detector technologies, whose role is to measure and constrain the neutrino flux and provide an accurate near to far detector spectrum prediction. A key component of the ND complex is ND-LAr - the only LArTPC in the detector suite. Sharing the same nuclear target and employing a similar detector technology as the FD, ND-LAr is crucial in constraining the cross-section and detector modelling uncertainties.

2. The DUNE ND-LAr Detector Design

Several successful, large-scale LArTPCs have been deployed. This includes monolithic detectors such as ICARUS, SBND, MicroBooNE and ProtoDUNE-SP [3–6]. Traditionally, these are instrumented with a wire-based charge readout, which provides a number of 2D projections of the final state particles resulting from the underlying neutrino interaction. In the presence of a high interaction rate of $O(50)$ interactions per beam spill at ND-LAr this technology poses reconstruction ambiguities [7]. These arise due to charge deposits from multiple interactions overlapping in different projections. Moreover, the inherently slow nature of the charge readout in LArTPCs, constrained by the drift speed of electrons across the detector volume, requires the detection of prompt scintillation light to perform the so called charge-light matching as an important handle for particle identification and event reconstruction. The association of charge and scintillation light signals becomes intractable in a monolithic detector with the high event pile-up expected at ND-LAr.

In order to reduce the signal occupancy in the charge and light readout subsystems, ND-LAr is the first modularised LArTPC design based on the ArgonCube concept [8]. Arranged in a 7x5 array of individual detector modules (see Figure 1), each split into two volumes via a central cathode, it consists of 70 optically-isolated TPCs each with dimensions of 0.5 m×1 m×3 m. Each module consists of charge and light readout subsystems located on alternating faces of the volume (see Figure 1) all enclosed with a low-profile field cage, which minimises the inactive regions in between the TPCs [9].

True 3D imaging of charge deposits is enabled through the departure from a wire-based to a pixelated charge readout [10]. ND-LAr contains approx. 200 m^2 of LArPix anode tiles with a channel density of 64K channels/m^2 to achieve O(mm) spatial resolution and high-granularity images. The self-triggering digitisation of LArPix allows for continuous data readout while maintaining low

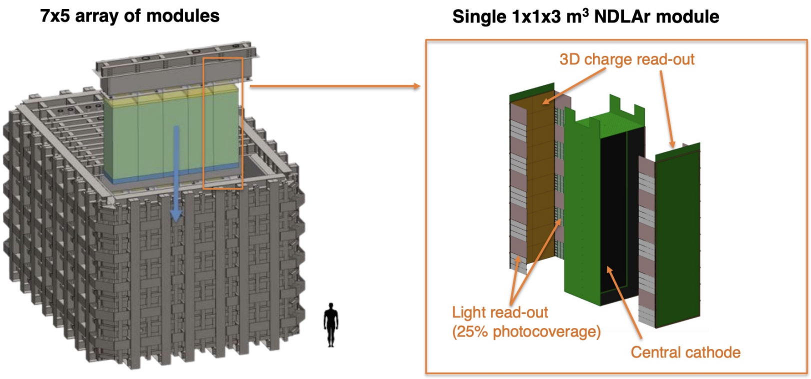

Figure 1: Left: Diagram of the ND-LAr detector. ND-LAr is composed of 7 rows of 5 individual detector modules. Right: Diagram of a single ND-LAr module. Each is divided into two optically-isolated LArTPCs via a central cathode. The ionisation electrons drift towards charge readout anode planes located on opposite faces. The detection of scintillation light is facilitated via light collection modules located on the two remaining faces. Each module is enclosed in a thin field shell made of a continuously resistive material. Figure adapted from [7].

data rates. Some of the key features of this technology are the low-power, low-noise data digitisation and readout as well as a dynamic chip network configuration which makes it robust to single point failures on the tile. The readout of the vacuum ultraviolet (VUV) scintillation light is enabled by two technologies, called ArCLight and LCM [11, 12]. They operate on a wavelength shifting light trap principle and are instrumented with SiPMs. Together, ArCLight and LCM provide high photocoverage of 25% and complementary features to observe high-fidelity light signals. In particular, ArCLight has a higher position resolution and a dynamic range, while LCM provides higher photon detection efficiency and, therefore, lower detection thresholds, as well as higher timing resolution.

3. The 2x2 ND-LAr Demonstrator

The 2x2 ND-LAr Demonstrator is the first fully-integrated O(kton) scale pixel-based modularised LArTPC. Consisting of a two-by-two arrangement of individual modules enclosed in a common cryostat, each approx. 60% the size of its ND-LAr counterpart, and containing O(100k) individual pixels, the 2x2 is the first DUNE detector prototype to observe GeV-scale neutrino interactions, facilitated by the NuMI beam [13].

The commissioning of individual 2x2 modules took place between 2021 and 2023 at the University of Bern. In total $O(100e6)$ cosmic-ray events were collected, allowing for first characterisation and performance demonstrations of the novel technologies [14]. During these operations, the charge readout observed a stable data rate with a 20:1 signal-to-noise ratio and was continuously active in self-triggering mode with a threshold as low as 200 keV. The light readout photon detection efficiency was measured to be 0.6% and 0.2% for LCM and ArCLight, respectively [15]. In addition, the analysis of data from LCM showed the ability to observe energy deposits as small as 1.6 eV and a timing resolution approaching 2 ns for 200 photoelectron signals.

The installation and commissioning of the 2x2 ND-LAr Demonstrator in the MINOS ND hall at Fermilab concluded in the summer of 2024. In order to efficiently tag and reject the muon backgrounds originating from neutrino interactions in the rock surrounding the detector cavern, tracking planes from the MINERνA experiment were repurposed and installed upstream of the 2x2 cryostat [16]. Due to its modest size compared to the spatial extent of the final state topologies resulting from NuMI neutrino interactions within the detector volume, the modularised LArTPC faces acceptance challenges. To mitigate those, a number of MINERνA planes are also located downstream of the cryostat to serve as muon taggers and muon/pion discriminators.

After a successful ramp-up to the nominal field of 500 V/cm, the 2x2 + MINERνA setup has successfully completed its first NuMI run observing antineutrinos at a rate of 0.3 million charged-current interactions per year. With the charge collection system operating with >97% channels active and at 200 keV thresholds, and the light readout fully active, 5 days of high-purity, physics-quality $\bar{\nu}_\mu$ data has been collected. Figure 2 presents one of the first neutrino events detected. A subsequent analysis of the data will follow. Key technical demonstrations include:

- Native 3D processing and reconstruction of data using a comprehensive software stack.
- Correlation of energy deposits across various LArTPC volumes and different detector technologies.
- Assessment of how inactive regions affect energy bias.
- Analysis of charge-light matching capabilities to address and reduce charge pile-up issues.

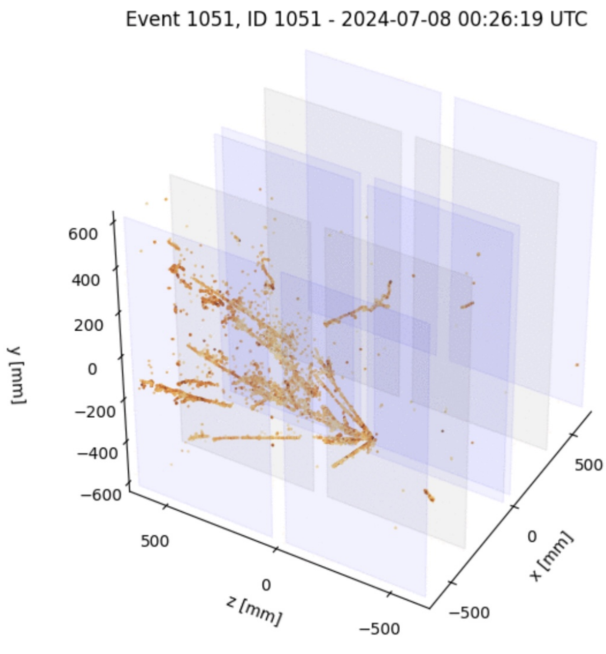

Figure 2: An event display of a high-multiplicity neutrino interaction observed during the 2x2 commissioning. This is one of the first neutrino interactions to be digitised natively in 3D in a LArTPC.

Further to the technical goals outlined above, the 2x2 operations present a unique opportunity for a physics program. Sampling a region of phase-space in high invariant mass on argon that is not only relevant to the energy regimes probed by DUNE, but also largely unexplored, its data will provide information complementary to that of other LArTPC experiments such as SBND and ICARUS. This includes the potential to study interactions for which the data are scarce, such as antineutrino scattering or charged pion production channels, and to probe high-multiplicity charged track final-states that are sensitive to final-state interaction modelling. In addition, the combination of the underground location, the continuously active charge collection system, and low operational thresholds offer a possibility of physics studies outside the neutrino interaction paradigm, such as beyond the Standard Model searches and non-beam studies.

4. Summary

The Deep Underground Neutrino Experiment (DUNE) is a future long-baseline accelerator neutrino experiment designed to achieve high-precision measurements of neutrino oscillations. It features a powerful >2 MW beam, a near-detector (ND) at Fermilab, and a far-detector (FD) located in Lead, South Dakota. Central to DUNE's precision is the ND, which includes the ND-LAr detector, the only liquid argon time projection chamber (LArTPC) in the suite. ND-LAr's modular design, featuring 70 optically-isolated TPCs and novel readout technologies (LArPix for native 3D charge readout and light collection modules ArCLight and LCM), addresses the challenge of high interaction rates at the ND. The 2x2 ND-LAr Demonstrator, ND-LAr's fully-integrated prototype, has successfully begun operations, collecting 5 days worth of physics-quality $\bar{\nu}_\mu$ data. It will demonstrate robust event reconstruction capabilities using the first-of-its-kind LArTPC design and deliver its own broad physics program.

References

[1] DUNE collaboration, A. Abed Abud et al., *Low exposure long-baseline neutrino oscillation sensitivity of the DUNE experiment*, Phys. Rev. D 105 (2022) 072006.

[2] DUNE collaboration, B. Abi et al., *Long-baseline neutrino oscillation physics potential of the DUNE experiment*, Eur. Phys. J. C80 (2020) 978.

[3] ICARUS collaboration, S. Amerio et al., *Design, construction and tests of the ICARUS T600 detector*, Nucl. Instrum. Meth. A527 (2004) 329.

[4] SBND collaboration, R. Acciarri et al., *Construction of precision wire readout planes for the Short-Baseline Near Detector (SBND)*, JINST 15 (2020) P06033.

[5] MicroBooNE Collaboration, R. Acciarri et al., *Design and Construction of the MicroBooNE Detector*. JINST 12 (2017) P02017.

[6] DUNE collaboration, B. Abi et al., *First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform*, JINST 15 (2020) P12004.

[7] DUNE collaboration, A. Abed Abud et al., *Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report*, Instruments 5 (2021) 31.

[8] J. Asaadi, et al., *A New Concept for Kilotonne Scale Liquid Argon Time Projection Chambers*, Instruments 4 (2020) 6

[9] R. Berner, et al., *First Operation of a Resistive Shell Liquid Argon Time Projection Chamber: A New Approach to Electric-Field Shaping*, Instruments 3 (2019) 28.

[10] D.A. Dwyer, et al., *LArPix: demonstration of low-power 3D pixelated charge readout for liquid argon time projection chambers*, JINST 13 (2018) 10007.

[11] M. Auger, et al., *ArCLight – A Compact Dielectric Large-Area Photon Detector*, Instruments 2 (2018) 3.

[12] N. Anfimov, et al., *Development of the Light Collection Module for the Liquid Argon Time Projection Chamber (LArTPC)*, Instruments 15 (2020) 0702.

[13] S.E. Kopp, *The NuMI Beam at Fermilab*, arXiv:physics/0508001 [physics.acc-ph]

[14] DUNE collaboration, A. Abed Abud et al., *Performance of a modular ton-scale pixel-readout liquid argon time projection chamber*, Instruments 8 (2024) 41.

[15] A. Gauch, *Scintillation light detection performance for the DUNE ND-LAr 2×2 modules*, JINST 18 (2023) C04004.

[16] MINERνA collaboration, L. Aliaga et al., *Design, calibration, and performance of the MINERνA detector*, Nucl. Inst. and Meth. A743 (2014) 130.