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The 2 × 2 Demonstrator: A demonstrator for the DUNE ND-LAr Near Detector based on the ArgonCube Design

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The Deep Underground Neutrino Experiment (DUNE) is a next generation long-baseline neutrino oscillation experiment designed to observe neutrino and antineutrino oscillation patterns to precisely measure neutrino mixing parameters. DUNE near detectors will measure and constrain the neutrino flux and constrain the response for a near-far detector oscillation measurement. The 2×2 Demonstrator is a demonstrator for the DUNE ND-LAr near detector based on the ArgonCube design. The 2×2 Demonstrator will characterize neutrino-Argon interactions in the few-GeV regime. Composed of a 2-by-2 grid of four optically segmented LArTPC modules sandwiched between upstream and downstream repurposed MINERνA tracking planes, each TPC module has a footprint of 0.7 m by 0.7 m and is 1.4 m tall. The 2.4 metric ton LAr active mass is instrumented by 337k charge-sensitive pixels at 4 mm pitch and thin-profile scintillation traps for 25% optical coverage. The detector will acquire antineutrino data in 2024 in the NuMI beamline at Fermilab, marking the first neutrino physics data for the ArgonCube detector concept from which the DUNE near detector modular LArTPC (ND-LAr) design is predicated. Roughly 300k charged-current active volume fiducialized antineutrino vertex interactions are expected per year in NuMI medium energy RHC operation. In addition to the copious GeV-scale neutrino interactions, physics analysis worthy data at the MeV-scale is possible, leveraging the near 100% uptime free-streaming, few hundred keV charge readout pixel trigger thresholds. Key technical demonstrations including 3D reconstruction of neutrino signals, track-matching with external trackers, and charge-light signal correlations in a high intensity neutrino beam will be exercised to assess ND-LAr design efficacy. A system design overview and status are reported.

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1. Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation accelerator-based long-baseline neutrino oscillation experiment designed to precisely measure all parameters governing ν_1–ν_3 and ν_2–ν_3 mixing to high precision. DUNE is composed of a broadband neutrino beam (LBNF beamline) and near detector (ND) located in Batavia, Illinois, USA and a far detector (FD) 1,285 km away in Lead, South Dakota, USA. Irrespective of the underlying true neutrino mixing parameter values, DUNE is designed to unambiguously resolve the neutrino mass ordering at the 5σ-level with 100 kt-MW-CY FD exposure [1]. DUNE has the potential to observe charge-parity violation in the lepton sector at 3σ precision for 75% of δ_{CP} values with 1104 kt-MW-CY FD exposure [2].

A capable, highly-performant ND is required to realize the DUNE design. The role of the ND in the long-baseline neutrino oscillation physics program is two-fold: first, to measure and constrain the neutrino flux from the LBNF beamline; and second, to constrain the response for a near-far detector oscillation measurement. The ND is composed of a suite of detectors[1], where design principles [3] have been informed by the current-generation long-baseline neutrino oscillation experiments T2K [4] and NOνA [5]. The ND-LAr detector — the single-phase liquid argon time-projection chamber (LArTPC) component of the ND — is functionally similar to the FD with an identical liquid argon nuclear target, serving as a direct constraint on FD detector- and $\overset{(-)}{\nu}$–Ar interaction-level uncertainties. To meet the systematic uncertainty budget in long-baseline neutrino oscillation analyses, high fidelity reconstruction of neutrino interactions in ND-LAr is imperative.

2. Module Design

ND-LAr requires a LArTPC design that is resilient to beam neutrino pile-up. For a typical ~10 μs-wide LBNF beam spill at 1.2 MW beam power, a mean of 55 neutrino interactions (with incident neutrino vertices both internal, 57%, and external, 43%, to the LArTPC) produce ionization and scintillation signals within the 105 m^3 active volume. To enhance neutrino interaction reconstruction by reducing light pile-up[2] and simplifying light-charge signal association combinatorics[3], the ND-LAr detector is optically segmented with a modularized LArTPC [7] — the *ArgonCube* detector concept. Optically segmenting the detector volume into 70 TPCs (each TPC sized at 50 cm × 100 cm × 300 cm) results in a mean of 5 scintillation signals per TPC per spill.

An optically segmented LArTPC is a vast departure from the archetypal monolithic active volume projective charge readout LArTPC common to many large scale $\mathcal{O}(100)$-tonne LArTPC detectors [8–11]. Limiting inactive volumes within and between modules while maintaining high signal fidelity necessitated novel hardware development. From 2016 – 2019, component technology R&D on low-profile field cage [12], high-photocoverage/low-profile VUV light traps [13, 14], and true 3D pixelated readout [15] indicated prospective viability of the modular LArTPC design.

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[1] See [6] for a detailed description of the ND complex.

[2] Assuming a scintillation time resolution of 25 ns, the rate of optical signal pile-up is 3% per module per spill, relative to 30% for a monolithic detector of equal size.

[3] With modest resolutions for both scintillation signal amplitude and position within the module, the corresponding ionization signals in each module can be accurately time-tagged and thereby algorithmically associated to the correct neutrino interaction.

The first fully-integrated 60%-scale module prototype operated in Spring 2021 at the University of Bern, successfully imaging cosmic-rays [16]. See the left-hand side of Fig. 1 for a 3D CAD representation of the 60%-scale LArTPC module prototype. Four individual 60%-scale module prototypes have been performance qualified through LArTPC operation at the University of Bern, collecting roughly 100 million cosmic ray events. An example cosmic ray event is displayed on the right-hand side of Fig. 1.

Each module was instrumented by $O(100\text{k})$ pixel channels, where each pixel has a uniquely addressable readout. Native 3D imaging with millimeter-granularity was achieved by the LArPix-v2 end-to-end charge readout pixelation system [17] instrumentation of each TPC anode. The charge readout was operated with nearly 100% up-time, operating in self-triggered mode. Individual pixel thresholds were typically set at about 4,000 electrons, corresponding to roughly 200 keV per channel threshold. MIP response exceeded 20:1 signal-to-noise and was demonstrated to be stable through the course of data taking and consistent with expectation [18].

Thin-profile VUV sensitive light traps tile vertical field cage panels normal to the anode for 25% optical coverage. Two complementary light traps are deployed, the ArCLight (ArgonCube light detector) and LCM (light collection module), sharing common readout electronics. Photon detection efficiency (PDE) was evaluated to be ~0.6% and ~0.2% for LCM and ArCLight, respectively [19]. With a large photosensitive area, the ArCLight has demonstrated a spatial resolution of ~5 cm; the LCM spatial resolution is defined by a singule device unit width, ~10 cm. For ~200 photoelectron scintillation signals, ~2 ns timing resolution has been demonstrated between two LCM light traps.

Cosmic ray sample data analysis has validated charge readout 3D imaging fidelity and performant light readout timing and spatial resolution, corroborating the expected performance of the single module design. To evaluate the ArgonCube detector concept, a high occupancy environment akin to the signal pile-up expectation of the LBNF-beam is required.

3. 2 × 2 Demonstrator

The 2 × 2 Demonstrator is a technical demonstrator of the ArgonCube detector concept. The detector consists of four 60%-scale optically-segmented LArTPC module prototypes in a 2-by-2 array sharing a common cryostat. See the left-hand side of Fig. 2 for a 3D representation of the 2 × 2 Demonstrator. The 2 × 2 Demonstrator will sample the NuMI medium energy beamline [20] in an on-axis position from the underground MINOS ND hall at Fermilab, characterizing GeV-energy $\overset{(-)}{\nu}$ interactions on Ar nuclei. Although the anticipated LBNF flux is significantly more intense than that provided by the on-axis medium energy NuMI flux (see the right-hand side of Fig. 2), the measured interaction rate at the 2 × 2 Demonstrator is expected to be comparable to that expected at ND-LAr due to $\overset{(-)}{\nu}$-nuclei cross section dependence on $\overset{(-)}{\nu}$ energy.

The 2 × 2 Demonstrator is book-ended by repurposed MINERνA tracking planes [21], to identify muons that pass through the 2 × 2 Demonstrator with neutrino vertex originating elsewhere. Given a relatively modest LAr active volume, the 2 × 2 Demonstrator exhibits final start particle acceptance challenges. MINERvA aids in mitigating these effects by serving as a muon tagger, with robust muon-charged pion discrimination power. The majority of 2 × 2 Demonstrator fiducial volume originating muons are anticipated to punch through MINERνA, precluding an accurate muon momentum measurement.

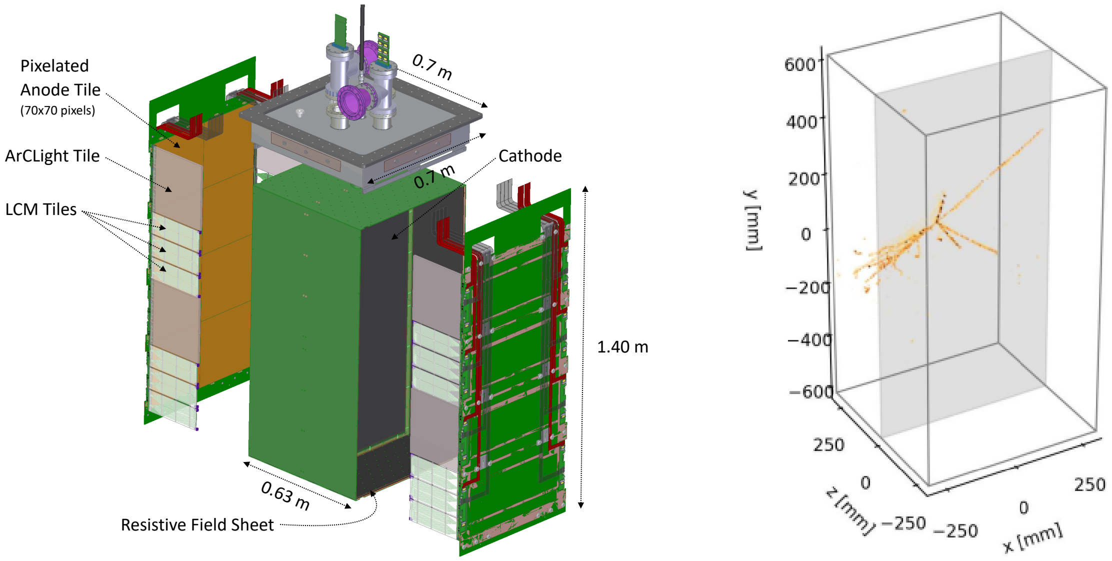

Figure 1: (Left) Annotated 3D CAD rendering of the 60%-scale ND-LAr module prototype. The module is 1.4 m tall with a footprint of 70 cm × 70 cm, with two adjoining TPCs. A central cathode bifurcates the module into 30-cm drift regions. The field cage consists of low-profile, custom resistive-film-on-fiberglass panels. Eight 31 cm × 32 cm large-format, low-profile LArPix-v2 pixel tiles populate each anode. At roughly 4 mm pixel pitch, each module is instrumented by 78.4k (or 102.4k) pixel channels. With 25% photocoverage, the module is operated by 16 low-profile VUV sensitive light traps. Eight ArCLight (wavelength shifter embedded plastic with dimensions 1 cm × 30 cm × 30 cm) and eight LCM (wavelength shifter embedded fiber bundle with dimensions 1 cm × 10 cm × 30 cm; 3 units comprise an LCM tile) light traps are vertically interleaved, abutting the inner wall of the vertical field cage panels. In total, 96 SiPMs per module couple to light trap devices for VUV down-shifted scintillation light detection. (Right) Neutrino-like cosmic ray interaction imaged in a 60%-scale module prototype. Raw data is displayed without signal processing or filtering. Each point is a self-triggered, digitized hit recorded by an individual pixel. The gray plane denotes the central cathode which bifurcates the drift volume. The LAr active volume is represented by the confining rectangular prism, spanning roughly 60 cm × 60 cm × 120 cm.

2×2 Demonstrator operation in NuMI will provide invaluable insight to evaluate integrated detector performance and inform final ND-LAr detector design. Key technical demonstrations germane to the DUNE long-baseline neutrino oscillation analysis include: (*a*) 3D reconstruction of visible neutrino interaction final state particles, (*b*) track matching with external trackers (e.g. MINERνA), (*c*) evaluation of the impact of un-instrumented detector volumes on reconstructed neutrino energy (E_{ν}^{reco}) bias, and (*d*) evaluation of charge-light signal association fidelity and the corresponding impact on E_{ν}^{reco} bias in a high signal occupancy environment.

In addition, compelling $\overset{(-)}{\nu}$–Ar cross section measurements are anticipated, complementing the existing measurements on Ar made by ArgoNeuT and MicroBooNE [22]. The 2×2 Demonstrator will sample unexplored phase space in hadronic invariant mass, largely inaccessible by SBND and MicroBooNE [23]. DUNE is anticipated to have a significant fraction of neutrino interactions with a high hadronic invariant mass. Producing more complex topologies with larger multiplcity of final states, this region of phase space is less theoretically mature relative to simpler topologies. Although many of these measurements have been experimentally characterized on other nuclear targets [24],

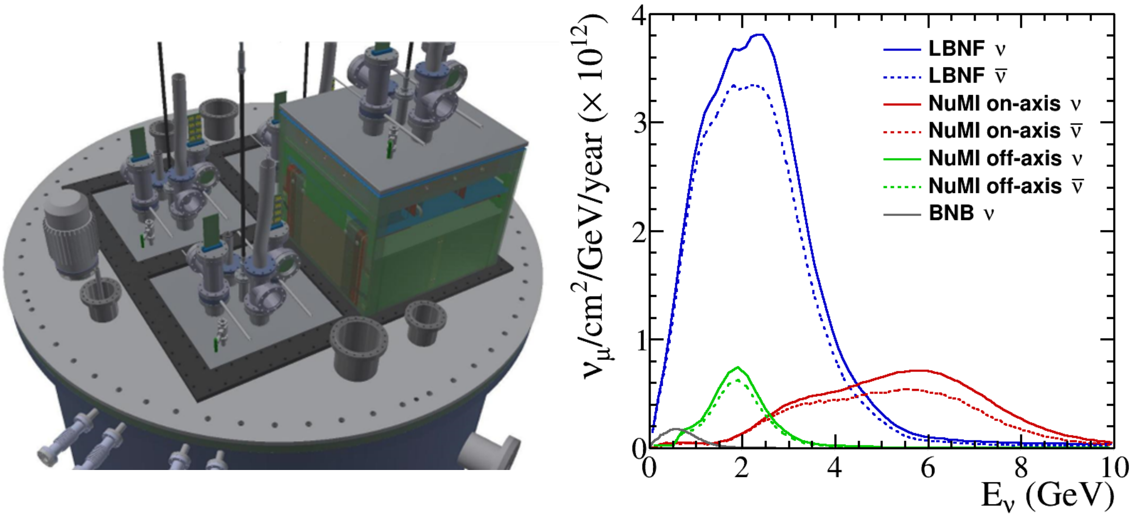

Figure 2: (Left) The 2×2 Demonstrator 3D CAD rendering. Each of the four 60%-scale module prototypes share a common cryostat in a 2-by-2 array. The 2.4 metric tone active mass is instrumented by 337.6k charge-sensitive pixel channels at roughly 4 mm pixel pitch. (Right) Absolutely normalized neutrino and antineutrino fluxes from FNAL-based accelerator-sourced neutrinos. Note the red spectra denote the medium energy NuMI configuration. Figure from [23].

there are a dearth of measurements with Ar nuclei. On-axis NuMI measurements from the 2×2 Demonstrator will be complimented by off-axis NuMI measurements from ICARUS [25] studying pion production. Initial 2×2 Demonstrator beam-operation is anticipated in RHC antineutrino-mode. Roughly 300k charged-current active volume fiducialized antineutrino vertex interactions are expected per year in NuMI medium energy RHC operation.

Moreover, in recent years, ArgoNeuT [26–30] and MicroBooNE [31, 32] have pioneered the breadth and versatility of LArTPCs for beyond the Standard Model (BSM) physics searches. Unique operating conditions at the 2×2 Demonstrator open up the possibility for novel BSM physics searches and characterization of rare Standard Model processes [33] like Cabbibo-suppressed Λ-baryon production as was observed at MicroBooNE [34]. With a 107 m rock overburden (300 m.w.e.), the charge readout is continuously active operating in self-triggering mode with $\sim$200 keV channel thresholds, opening up the possibility of competitive physics applications analyses with both on-beam as well as off-beam data.

4. Concluding Remarks

The 2×2 Demonstrator provides an opportunity to assess the ArgonCube detector concept in a LBNF-like high intensity environment. In addition to technical performance demonstrations, the 2×2 Demonstrator physics program is rich and diversified with on-beam and off-beam physics ranging from the MeV- to the GeV-scale. MINERνA tracker plane modules have been re-commissioned, recording NuMI neutrino data since Spring 2023. 2×2 Demonstrator cosmic-ray operation is anticipated to commence in early 2024, with NuMI RHC-mode beam delivery anticipated shortly after.

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