PROCEEDINGS OF SCIENCE

A Gaseous-Ar Based Near Detector (ND-GAr) for DUNE Phase II

Tanaz Mohayai, on behalf of DUNE[a,*]

[a] *Department of Physics, Indiana University,*
107 S Indiana Ave, Bloomington, IN United States

E-mail: tmohayai@iu.edu

The Deep Underground Neutrino Experiment (DUNE) is a next-generation experiment that aims to make high-precision measurements of neutrino mixing parameters and search for Beyond Standard Model (BSM) signatures. DUNE Phase II will include an upgrade to a high-pressure gaseous argon TPC, known as ND-GAr or the More Capable Near Detector (MCND) in DUNE's near detector complex. With its fine-grained tracking capability and low detection threshold, ND-GAr will play a key role in reducing systematic uncertainties related to nuclear effects in argon, which are critical for neutrino oscillation measurements, and will also enhance searches for BSM physics. This paper will highlight the ND-GAr design, its performance expectations, and the ongoing R&D efforts for various readout systems, including wire chambers and Gas Electron Multipliers (GEMs).

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*Speaker

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1. Introduction

Phase II of DUNE [2] is essential for realizing the full scope of DUNE. It includes upgrades to the Near Detector (ND), Far Detector (FD), and beam to enhance sensitivity for key measurements, such as CP violation and BSM searches. A primary objective of these upgrades is to address a critical challenge faced by existing neutrino oscillation experiments: reducing uncertainties in neutrino interaction cross-sections. While NOvA and T2K [3, 4] have reduced these uncertainties to approximately 4% and 5%, respectively, DUNE requires percent-level precision, particularly in modeling low-energy hadronic activity at the neutrino interaction vertex. To meet this challenge, as recommended by the P5 report [1], DUNE's Phase II ND upgrade will consist of a high-pressure gaseous argon detector, combined with a magnetic field and electromagnetic calorimeter system, called ND-GAr or MCND. As shown in Fig. 1, without the upgrade to ND-GAr or MCND to replace Phase I's muon spectrometer (TMS), DUNE will fall short of achieving 3σ sensitivity for 75% of δCP values (left plot). However, with the ND upgrade to ND-GAr/MCND, 5σ sensitivity for 50% of δCP values can be reached within approximately 5 years of installing ND-GAr (right plot).

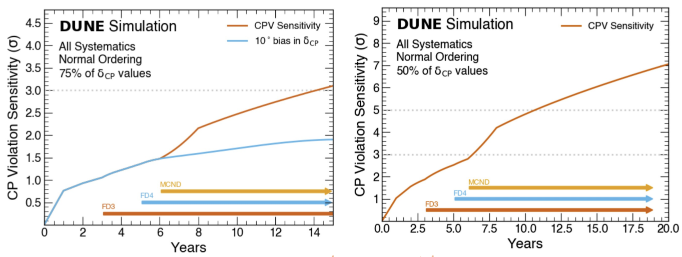

Figure 1: Sensitivity plot illustrating the need for the full scope of DUNE through Phase II upgrades to ND, FD, and beam. The ND upgrade to MCND/ND-GAr is especially critical for constraining systematic uncertainties. [5].

2. The Specific Advantages of a Pressurized Gaseous-argon Based Near Detector

Systematic uncertainties in neutrino interactions mainly stem from the limited ability to estimate the neutrino energy spectrum. Neutrino energy has to be inferred from the energies of the outgoing lepton and hadrons, but challenges persist in predicting the energies of low-energy hadrons produced in neutrino interactions. Neutrino interaction models attempt to predict these low-energy hadrons; however, as shown in the plot in Fig. 2, there are disagreements between different models in various neutrino generators. The dashed line in the figure represents the threshold for detecting a 1 cm proton track in a liquid argon detector, while the solid line represents the significantly lower threshold in a high-pressure gaseous argon detector. With the same pixelization level in the readout electronics, the energy threshold for the same proton track is approximately 15 times lower in the high-pressure gaseous argon detector. A low-energy threshold detector is therefore essential for exploring this problematic energy region, as it provides crucial data for refining and tuning interaction models. Furthermore, accurate reconstruction of low-energy hadrons could reduce reliance on interaction models for neutrino energy estimation, as the hadronic energy can be directly summed for many interactions. A gaseous argon-based detector like ND-GAr is also crucial for probing BSM physics, with its large magnetized volume which aids in searches of rare decays and its low mass which minimizes neutrino scattering backgrounds to these searches [2].

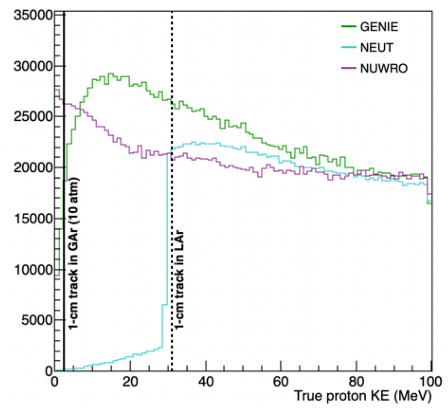

Figure 2: The high-pressure gas TPC is essential for probing low-energy protons, where neutrino event generators often struggle to predict proton energies accurately. These discrepancies introduce uncertainties in hadronic energy measurements, which can bias neutrino energy estimates and impact key DUNE measurements, such as the CP-violating phase. [6].

3. Design of a High-pressure Gaseous Argon TPC and its On-going R&D Thrusts

At its core, ND-GAr design features a high-pressure gas argon time projection chamber (TPC) capable of recording over one million muon neutrino interactions annually in a 1-ton fiducial volume. Surrounded by a magnet system and an ECAL calorimeter, the TPC is designed to operate at 10 atmospheres within a 5-meter diameter and length. The high-pressure gas enables more ionization electrons per track length, providing excellent PID resolution, and it offers 4π acceptance. However, operating TPCs at high pressure poses challenges for modern readout systems, necessitating extensive R&D in amplification, electronics, and gas mixture optimization.

To address this, initial tests were carried out on multi-wire proportional chambers (MWPCs) acquired from the ALICE TPC, providing a critical basis for characterizing amplification systems in high-pressure gas argon mixtures. The ALICE MWPCs, which have safely operated up to 3,000 V in ALICE, were tested under pressure in two setups: the Test of an Overpressured Argon Detector (TOAD) at Royal Holloway and Gaseous-argon Operation of ALICE TPC (GOAT) at Fermilab. TOAD tested an ALICE Outer Readout Chamber (OROC) at 4 bar, while GOAT tested an ALICE Inner Readout Chamber (IROC) at 10 bar. As shown in Fig. 3, increasing pressure requires higher voltages to maintain consistent gain (left plot). GOAT's tests with an Ar-CO2 mixture (with molar ratios of 90% and 10% of Argon and CO_2) required voltages above 3,000 V for gains above 100, but replacing CO2 with smaller CH_4 admixtures allowed gains of 1,000 at safer voltage levels < 3,000 V (right plot).

Additional testing of amplification systems is underway at Fermilab and Indiana University through testing of GEMs. These tests are born out of a Fermilab New Initiatives award [8]. The GORG (GEMs Overpressured with Reference Gases) setup, used for the initial tests at Fermilab, is

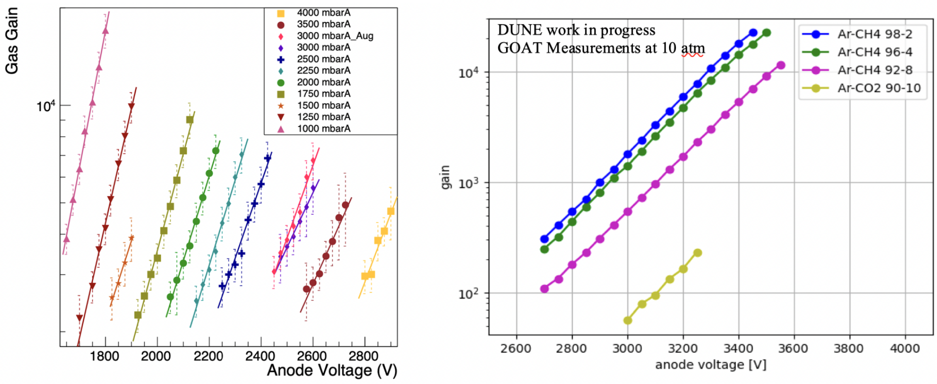

Figure 3: Gas multiplication gain results for the TOAD setup (left) [7] and GOAT setup (right).

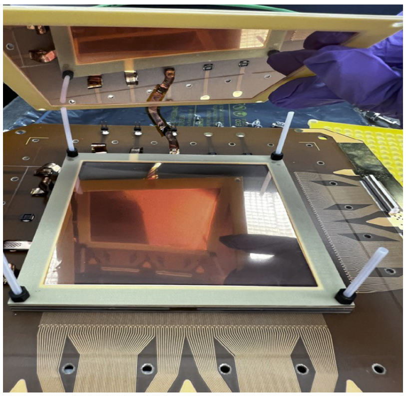

Figure 4: The close-up photo shows the GEMs in the GORG setup at Fermilab, along with the readout board, which includes two sets of 64 strips for both the x and y orientations. Initial tests used a Panasonic-to-Lemo adapter to chain and read out 64 strips at a time (credit: the Indiana University group).

shown in Fig. 4. As part of the GORG setup, standard triple-GEMs, procured in collaboration with Techtra TTA [9], have been tested at 1 atm in two argon mixtures: one with 10% CO_2 and another with 8% CH_4 admixtures. The CH_4 mixture provides better voltage stability, delivering up to 3,300 V to a voltage divider which delivers 360 V, 310 V, and 271 V to the three GEM layers. Transfer gaps in each GEM layer are set to 1 mm and 2 mm, with the induction and drift gaps at 1 mm and 2 mm. The goal is to optimize the gaps, gas mixtures, and voltage distributions to the GEM layers for maximum gain at 1 atm before moving to high-pressure tests. Preliminary results with the Fe-55 calibration source (Fig. 5) for the Ar-CH_4 (92%:8%) mixture are promising, with ongoing work to reduce noise and improve the pulser calibration peak (shown in pink in Fig. 5) to calculate the reference electronics gain and multiplication gain. In the meantime, the GOAT pressure vessel has been re-approved for high-pressure tests at Fermilab, and the GORG setup will move there after the planned optimizations. Additionally, there are plans to carry out parts of the studies at the Indiana University pressure vessel that is being procured. Simulation studies are also ongoing to predict the performance of the triple-GEM structure at high pressure.

In parallel with TPC amplification development, ongoing tests of the readout electronics are being conducted using SAMPA-based cards connected to the back of an ALICE OROC. These tests

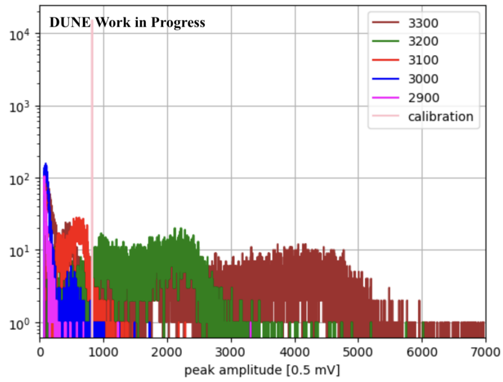

Figure 5: Fe-55 spectrum with the GORG setup shows the shifting of the main Fe-55 5.9 keV photopeak to higher amplitudes as the voltage supplied to the GEMs increases. The calibration can be used as a reference point in calculating the gain. On-going optimizations are underway before the setup moves to the GOAT pressure vessel.

were carried out in TOAD at the Fermilab Test Beam Facility (FTBF). The cards are internally routed to Power, Aggregation, and Timing (PAT) boards, shown in Fig. 6 minimizing the number of feedthroughs on the pressure vessel. The slice tests of the full chain of readout electronics are the first high-pressure tests of the complete readout electronics system for DUNE ND-GAr, successfully characterizing noise levels and the effects of electronics on temperature and pressure variations in the gas mixtures. The data on the pressure and temperature variations can also provide critical input for developing an electronics cooling system suitable for high-pressure operations of the electronics. Discussions have also begun on integrating these existing electronics with the ongoing GEM tests in the GORG setup.

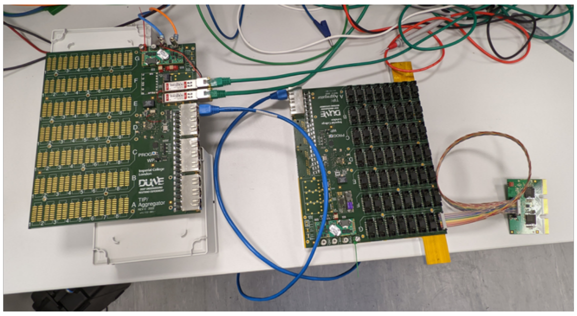

Figure 6: SAMPA-based cards connected to the back of the OROC are routed to PAT cards internally, passing through feed-throughs on the pressure vessel from right to left (credit: the Imperial College London group).

In addition to charge amplification R&D, studies are also focused on enabling the simultaneous readout of both charge and light signals in the TPC. Various gas mixtures are being evaluated, with particular attention given to those containing small ratios of CF_4 as a potential wavelength-shifting alternative to the more commonly used scintillation-quenching admixtures based on CH_4 and CO_2. A key part of this research is conducted at the Gas-Argon T0 (GAT0) technology demonstrator at IGFAE in Santiago de Compostela, Spain. GAT0 is performing experimental tests using THGEMs to investigate the properties and performance of these gas mixtures, which are potentially capable of providing both tracking [10] and time-stamping of interactions [11, 12] simultaneously. In parallel, simulation studies are underway to assess the feasibility and performance of Large-area Picosecond Photodetectors (LAPPDs) [13] within the ND-GAr detector.

4. Conclusion and Summary

The ND-GAr design offers unique capabilities for reducing systematic uncertainties in neutrino interaction cross sections and for enhancing the searches for BSM signatures in DUNE. With its low energy threshold, excellent PID, and 4π acceptance, ND-GAr will significantly enhance the precision of neutrino cross-section measurements, directly contributing to DUNE's goal of a 5σ sensitivity to CP violation for 50% of δCP values. There are ongoing R&D efforts on testing various components of the TPC in the high-pressure gas argon environment. These R&D efforts are essential for DUNE ND-GAr but through their novelty also benefit the greater detector community.

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