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ND-GAr: A novel high pressure gas TPC for DUNE(*)

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Summary. — The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino experiment aiming for precision measurements of neutrino oscillations. To control systematic uncertainties, DUNE employs a sophisticated Near Detector complex. Phase I will begin with a 1.2 MW beam, two FD modules, and a Near Detector suite including a liquid Argon TPC, a temporary muon spectrometer, and an on-axis beam monitor. Phase II will introduce upgrades: two additional FDs, a higher-power beam, and the replacement of TMS with ND-GAr —a high-pressure gas TPC offering low tracking thresholds and precise kinematic reconstruction. This contribution will highlight the unique capabilities of ND-GAr and its physics scope.

1. – Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino oscillation experiment [1]. Its primary objectives are to measure the parameters governing neutrino and antineutrino oscillations, with a focus on the CP-violating phase δ_{CP} and the neutrino mass ordering. The experiment will comprise three main components: a high-intensity, wide-band neutrino beam at Fermilab capable of producing both ν_μ and $\bar{\nu}_\mu$ fluxes; a multi-kiloton liquid argon Far Detector (FD) located 1300 km away at the Sanford Underground Research Facility (SURF) in South Dakota; and a modular Near Detector (ND) positioned ∼500 m from the source.

Due to budget constraints, DUNE will follow a staged construction and operation plan [2]. Phase I will consist of two 10 kt LArTPC FD modules using Vertical Drift (VD) [3] and Horizontal Drift (HD) [5] technologies. The ND complex will initially include two of its three planned components: ND-LAr, a modular LArTPC using a similar technology and target to the FD modules, and the System for On Axis Neutrino Detection (SAND), which will serve as a beam monitor [4]. Between them is The Muon Spectrometer (TMS), which is envisioned to be replaced in Phase II.

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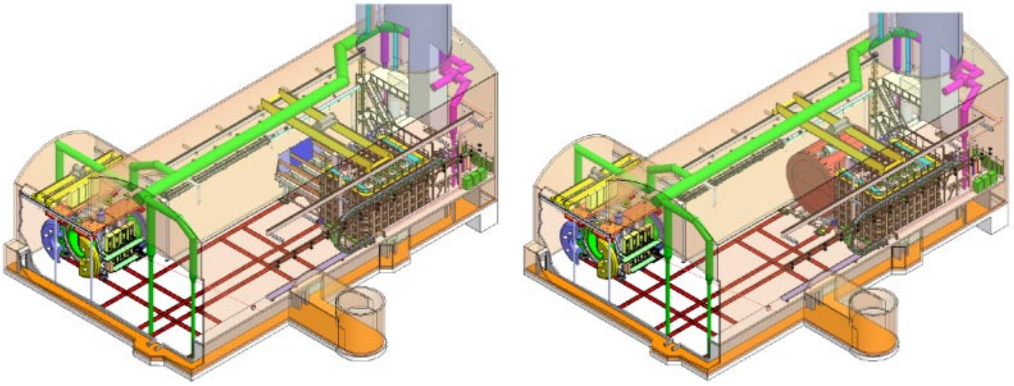

Fig. 1. – Layout of the envisaged Phase I (left) and Phase II (right) ND suite. The neutrino beam enters from the bottom-right corner, and exits at the top-left corner, of the drawings. The SAND detector is shown at its permanent on-axis location, while all other detectors upstream are shown at their maximum off-axis location [6].

To realize its full physics program, DUNE will implement major upgrades in Phase II. The FD will gain two additional LArTPC modules, increasing the total fiducial mass to at least 40 kt. The proton beam power will be raised from 1.2 MW to 2.3 MW. TMS will be replaced by ND-GAr, a magnetized high-pressure gaseous-argon detector.

These proceedings will be articulated as follows: in sect. **2** we will provide a discussion of the staging scenario between Phase I and II; in sect. **3** we will provide a description of the ND-GAr detector, articulating its physics goals and current design status; finally we'll summarize the main take-aways from this discussion in sect. **4**.

2. – DUNE staging

Budgetary constraints will require the DUNE experiment to pursue its physics program in two distinct phases. The overall configurations of the experiment in Phases I and II are summarized in table I and schematic representations of the ND hall are shown in fig. 1.

DUNE Phase I is expected to begin taking physics data with the FD in the late 2020s, with the beam and ND becoming operational by 2032 [2, 6]. The average beam

Table I. – *A high-level description of the two-phased approach to DUNE. The ND-LAr detector, including its capability to move sideways (PRISM), and the SAND are present in both phases of the ND* [6].

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

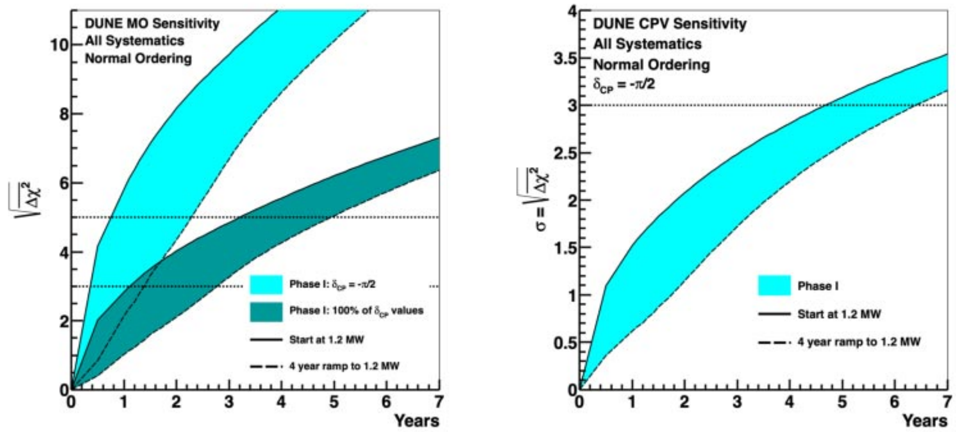

Fig. 2. – Sensitivity to the neutrino mass ordering (left) and CP violation for $\delta_{\mathrm{CP}} = -\pi/2$ (right) in Phase I. The cyan bands show the sensitivity if $\delta_{\mathrm{CP}} = -\pi/2$ and the green band in the left plot shows the sensitivity for 100% of δ_{CP} values. The width of the bands shows the impact of potential beam power ramp up; the solid upper curve is the sensitivity if data collection begins with 1.2 MW beam power and the lower dashed curve shows a conservative beam ramp scenario where the full power is achieved after 4 years [2].

power during the first year of beam operation will be 1.2 MW, increasing to 1.6 MW in the second year. Further optimizations are planned in subsequent years, with the beam power reaching 2.3 MW after approximately 15 years.

During the first three years of operation, DUNE will deploy two FD modules, providing a combined fiducial mass of 20 kt. The third and fourth modules (FD3 and FD4) are expected to become operational in years 4 and 6, respectively, bringing the total fiducial mass to 40 kt.

Systematic constraints from the Phase I ND will be applied through year 6. From year 7 onward, they will be progressively replaced by improved constraints from the Phase II ND. These updated constraints will be retroactively applied to previously collected FD data over a transition period of approximately two years.

Over five years of Phase I operation, DUNE is expected to accumulate roughly 100 kt·MW·yr of exposure, yielding approximately 400 ν_e and 150 $\bar{\nu}_e$ candidates in the FD, depending on oscillation parameters and assuming equal neutrino and antineutrino running. While statistically limited, this dataset —once corrected for Phase I ND systematics— will enable a determination of the neutrino mass ordering (MO) with significance exceeding 5σ, independent of the true oscillation parameters (fig. 2, left). If $\delta_{\mathrm{CP}} \simeq \pm\pi/2$, DUNE will also achieve a 3σ sensitivity to CP violation (CPV) (fig. 2, right). In addition, Phase I will yield improved measurements of Δm^2_{32} and $\sin^2 2\theta_{23}$, though its statistical power will not suffice to resolve the θ_{23} octant or confirm CPV in less favourable scenarios.

The full oscillation physics program requires an exposure of 600–1000 kt·MW·yr, depending on the measurement. This can be achieved with an additional 6–10 years of operation at > 2 MW beam power and a 40 kt FD, assuming systematics are controlled at the level provided by the Phase II ND. Without the increased beam power and detector

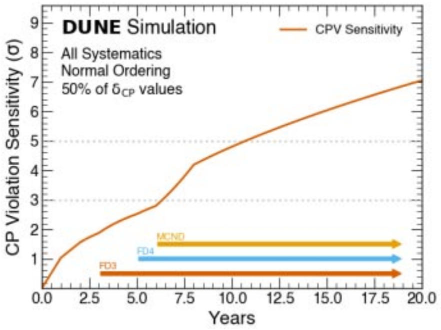

Fig. 3. – The significance for DUNE to establish CPV for 50% (left) and 75% (right) of δ_{CP} values as a function of running time [6].

mass, the same exposure would require 24–40 years. As shown in fig. 3, with the full Phase II exposure of 1000 kt·MW·yr, DUNE will achieve 3σ sensitivity to CPV for 75% of possible δ_{CP} values and measure δ_{CP} to within 6°–16°, depending on its true value.

3. – ND-GAr

In Phase II, the TMS will be replaced by ND-GAr, a magnetized high-pressure gaseous argon time projection chamber (HPgTPC) based detector. ND-GAr will serve as a spectrometer for particles exiting ND-LAr and will also provide an independent sample of neutrino interactions.

A key goal of the ND is to constrain neutrino-argon interaction models through identification of exclusive final states, particularly those involving pions. While ND-LAr will

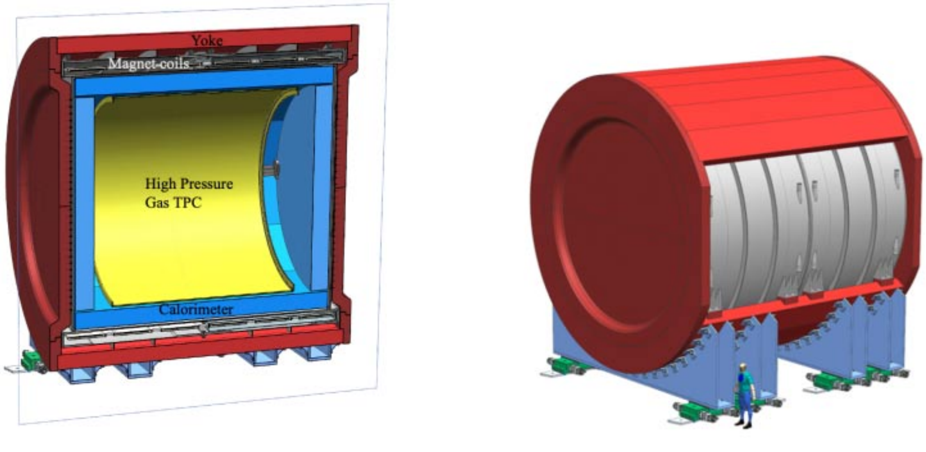

Fig. 4. – (Left) Cutaway view of the full ND-GAr detector system, showing the HPgTPC, the calorimeter, the magnet, and the iron yoke. The detectors for the muon-tagging system are not shown. (Right) The SPY magnet system. The hole in the yokes is on the upstream side, to minimize material traversed by tracks originating from neutrino interactions in ND-LAr [6].

be capable of reconstructing high-energy pions and protons well, low-momentum particles will often go undetected or be poorly measured due to inelastic scattering, decay, or short range. Protons below 300 MeV/c will be effectively invisible, and sub-threshold pions in the hundreds of MeV/c kinetic energy range, will deposit only a fraction of their energy. TMS will be capable of identifying muons below 6 GeV/c, but won't be able to resolve higher-energy muon charge or range.

The ND-GAr reference design includes a HPgTPC, a surrounding electromagnetic calorimeter (ECAL), a magnet, and a muon tagging system. A cutaway of the detector and an external view of the magnet are shown in fig. 4. The design is driven by the need to achieve the systematic control required for DUNE's physics goals beyond Phase I.

The gas environment, even at 10 bar will offer comparatively low tracking thresholds for pions, protons and nuclear fragments, producing longer tracks that can be more easily separated. In fig. 5 we show how an event is reconstructed in ND-LAr compared to ND-GAr, demonstrating the improvement in performance. Additionally, a magnetized TPC will offer sign selection and excellent particle identification, while also providing curvature-based momentum measurements for particles not contained in the detector. A gas TPC will also be able to measure neutrino interactions over all directions, unlike a LArTPC such as ND-LAr, for which acceptance is lost at high angles with respect to the beam direction. Finally, the pressurized environment will be capable of providing a significant amount of Argon target mass. Considering a pressure of 10 bar and diameter of roughly 5 m, ND-GAr's TPC would produce a fiducial mass of roughly a ton of Argon, yielding approximately a million neutrino interactions per year.

Several different readout technologies and gas mixtures are currently being considered for ND-GAr's HPgTPC. In all cases, a high-pressure gas mixture with high argon content ($> 90\%$ molar fraction) is envisaged, with a 96:4 Ar:CH_4 mixture having been successfully tested during ND-GAr's R&D. Multi-wire proportional chambers, decommissioned from

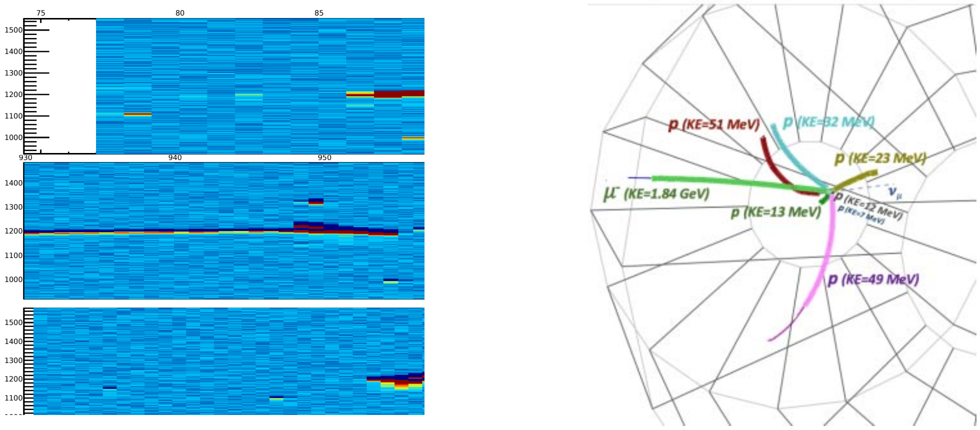

Fig. 5. – The same CC ν_μ event with seven low energy protons (kinetic energies ranging from 7 to 51 MeV) simulated in a LArTPC (left) and a HPgTPC (right). The LArTPC event display shows time ticks *versus* channel number for the three projective views of the event. The HPgTPC reconstruction algorithm finds all eight tracks in the event (seven proton tracks and one muon track), although only six are visible by eye in this view. All proton tracks travel 2.4 cm or less in LArTPC [6].

the ALICE experiment, have been tested using pressurized Argon gas at two separate test stands in the UK and US respectively [7]. The tests showed that acceptable gas gain performance could be achieved on the chambers, when operated at or above the high voltage levels used in ALICE. Despite this, the long-term operation and stability of these chambers at such high voltages remain to be investigated. Other solutions, using GEMs or "thick GEMs" (THGEMs) are also currently being investigated.

An attractive opportunity enabled by the heavy use of Argon in the TPC mixture is event time-tagging by way of scintillation light collection. Due to the complexity of the system, significant R&D efforts will be needed to study the level of localization necessary to associate time information with a given interaction. Recent efforts have focused on Ar-CF_4 mixtures, which have been shown to have strong and fast wavelength shifting properties, producing yields of 700-1400 photons/MeV. This has the potential to open up ns-level time tagging for energy deposits down to at least 5 MeV.

The current integrated design for ND-GAr's solenoid, pressure vessel, and yoke, is referred to as the Solenoid with Partial return Yoke (SPY). It consists of a superconducting magnet within an iron return yoke. To minimize size and cost, the magnet and cryostat are designed to form the cylindrical section of the HPgTPC pressure vessel and to support both the HPgTPC and the ECAL within their volume. Additionally the yoke is designed to include a hole on the upstream side, to minimize material traversed by tracks originating from neutrino interactions in ND-LAr.

The ECAL's main role within ND-GAr's sub-detectors roster will be to detect neutral particles, to which the HPgTPC is blind. For neutrinos in the DUNE energy range, these consist of mostly photons from pion decay and neutrons. The photon energy can be determined calorimetrically, while the neutron energy can be derived from the time of flight between the production vertex and nuclear re-scatter in the calorimeter. An affordable option currently being investigated consists of a plastic scintillator sampling calorimeter combining CALICE tile technology [8] with traditional strip-based SiPM readout.

4. – Conclusions

The DUNE experiment is set to greatly advance our understanding of neutrino flavour oscillations. The ND-GAr upgrade in Phase II will play a crucial role in reducing systematic uncertainties, particularly those related to neutrino-argon cross sections and nuclear effects. ND-GAr's HPgTPC, will provide excellent spatial resolution and access to low-energy kinematic regions, as well as a full acceptance, complementing the liquid argon detector ND-LAr. ND-GAr's innovative design is instrumental in ensuring the success of DUNE's scientific program, including measurement of CP violation and beyond.

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