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A novel optical imaging system for the LAr detector GRAIN(*)

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Summary. — The Deep Underground Neutrino Experiment will be a next-generation neutrino oscillation long-baseline accelerator experiment exploiting Liquid Argon Time Projection Chambers with the aim of determining the still unknown neutrino oscillation parameters, observing proton decay and detecting supernova neutrinos. GRAIN (GRanular Argon for Interactions of Neutrinos) is the Liquid Argon detector of SAND (System for on-Axis Neutrino Detection), which is part of the DUNE Near Detector complex. SAND is expected to significantly decrease uncertainties related to neutrino flux and cross-sections, to monitor the beam stability, and to investigate various neutrino interactions models, constraining at the same time nuclear effects. GRAIN will serve as a Liquid Argon target for detecting neutrinos and low-energy particles, ensuring cross-calibration with the other Near Detector components. The novel GRAIN system is designed to reconstruct charged particle tracks using the detection of LAr scintillation light by an optical system optimised for the Vacuum Ultra-Violet. Two options for the optical system are currently being studied: coded aperture masks and optical lenses, both coupled to a SiPM matrix. The readout, which is currently under development, will be performed through a 1024-channel ASIC, able to read 32x32 SiPM matrices in LAr.

1. – Introduction to the DUNE experiment

The DUNE experiment is a next generation long-baseline neutrino oscillation experiment under construction in the United States. It is divided into three central components: a high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab, a composite Near Detector (ND) installed just downstream of the neutrino source, and a multi-kiloton Far Detector (FD) based on Liquid Argon Time Projection Chambers (LArTPC), located 1.5 km underground at the Sanford Underground Research Facility in South Dakota, 1300 km away from Fermilab.

The project primary goals are the measurement of neutrino mass ordering and of the CP-violation phase, while also investigating various phenomena such as proton decay, core-collapse supernovas, solar neutrinos, and other Beyond Standard Model (BSM) physics.

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During its initial phase (Phase I), DUNE will employ a 1.2 MW proton beam [1], two Far Detector modules with a 20 kt Liquid Argon fiducial mass, and a temporary configuration of the Near Detector complex to achieve early physics objectives (refer to the Near Detector section for further details). However, to fully realize its scientific program in Phase II, DUNE will necessitate an upgraded 2.4 MW neutrino beam and a complete experimental apparatus, including four Far Detector modules (with at least 40 kt fiducial mass) and a Near Detector in its final configuration.

2. – The Far Detector

The DUNE Far Detector involves four LArTPC modules, each housed within a cryostat with a mass of approximately 17.5 kton each (10 kton fiducial mass) [2].

For DUNE Phase-I, only two modules are planned, exploiting single-phase LArTPC, with different technological implementations. One of them will be a traditional Horizontal-Drift LArTPC, while the other one will employ an innovative single-phase Vertical-Drift design where the cathode is placed at mid-height and the anode read-out is at the top and at the bottom of the cryostat. The designs for the third and fourth modules are yet to be determined.

3. – The Near Detector

The Near Detector complex will be located 574 m away from the source of the LBNF neutrino beam and 62 m underground in the DUNE ND hall, shown in fig. 1. It is supposed to measure and monitor the beam, constraining the flux and providing essential input for the neutrino interaction model. The Near Detector comprises three primary detector components: ND-LAr, ND-GAr, and SAND. According to the DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM) program, the ND-LAr and ND-GAr detectors can be moved sideways to study neutrino interactions with different energy spectra at different off-axis locations. It is planned that these two detector components will spend 50% of the time off-axis. SAND instead will be the only detector permanently on the beam axis, located in a dedicated alcove in the ND hall [3].

3·1. *ND-LAr*. – The ND-LAr detector is based on ArgonCube technology, consisting of a large TPC fabricated out of a matrix of smaller, optically isolated TPC modules. Since ND-LAr will be exposed to a much more intense neutrino flux than at the FD site, the subdivision of the volume will allow for smaller drift distances and times, which, together with the optical insulation, will reduce the issues with overlapping interactions.

3·2. *ND-GAr*. – The ND-GAr detector will be a High-Pressure Gaseous Argon TPC surrounded by an electromagnetic calorimeter within a 0.5 T magnetic field. It will provide muon momentum and charge reconstruction for events not contained within the ND-LAr volume together with an independent sample of neutrino interactions on Argon. ND-GAr is foreseen to operate during DUNE Phase II, replacing the TMS detector. The design of TMS is based on magnetised steel planes interleaved with scintillator strips.

3·3. *SAND*. – The third component of the ND suite is the System for On-Axis Neutrino Detection (SAND), a multi-purpose detector which will be permanently in the on-axis position. It will monitor the flux of neutrinos going to the FD, control systematic uncertainties for the oscillation analysis, and perform a rich neutrino physics program,

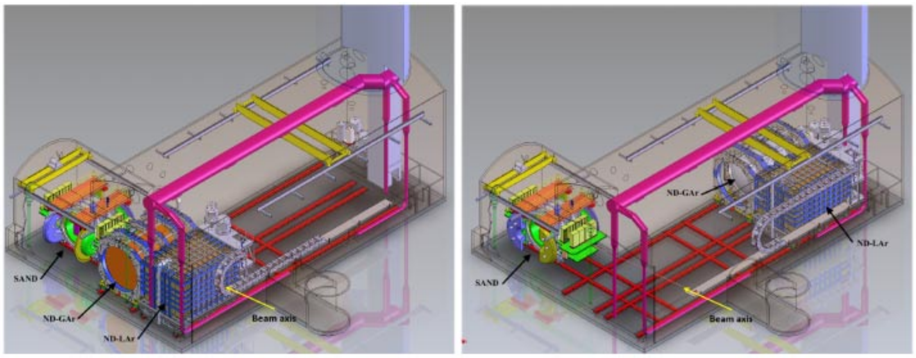

Fig. 1. – 3D view of the DUNE Near Detector hall. Left: all detectors are in the on-axis position. Right: ND-LAr and ND-GAr are moved off-axis [3].

including precision measurements of neutrino cross-sections [3]. SAND consists of several components:

- The superconducting magnet, previously operated in the KLOE experiment, producing a 0.6 T magnetic field [4].
- The electromagnetic calorimeter (ECAL), also refurbished from the KLOE experiment [4] and located inside the magnet. It is a lead scintillating fiber sampling calorimeter read-out by phototubes. The energy and time resolution of the calorimeter were evaluated in the KLOE commissioning and operation phases, being [5]: $\sigma/E = 5\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 54/\sqrt{E(\mathrm{GeV})}ps$
- The Straw Tube Tracker (STT), located inside the ECAL cylindrical barrel and designed to be a fully modular detector. It will be able to accommodate various target materials, such as C, CH_2, Ca, Fe, Pb, etc, physically separated from the effective tracking system (the straws), to extrapolate crucial information about neutrino-nucleon interactions.
- The LAr active target GRAIN.

4. – GRAIN

GRanular Argon for Interaction of Neutrinos is a ~ 1 t liquid Argon Active Target that will be placed upstream in the magnetized volume of SAND. GRAIN will provide inclusive Ar interactions to constrain systematic uncertainties from nuclear effects. Being permanently located on-axis, it will ensure cross-calibration with the other detectors. The cryostat will consist of two coaxial cylindrical-shaped vessels with an elliptical base, arranged horizontally so that the neutrino beam passes through it along the minor axis of the ellipse (see fig. 2).

The design is optimized to minimize the vessel material, resulting in a thickness of a small fraction of radiation length. The overall depth of the LAr volume is kept to a minimum (1 interaction length) to reduce energy loss, showering, and multiple scattering, as the outgoing particles will be analyzed by the downstream detector elements.

At the ND site, the expected neutrino interaction rate is 0.135 events/ton/spill, resulting in a total number of events in the entire SAND detector of about 83.5 events/spill.

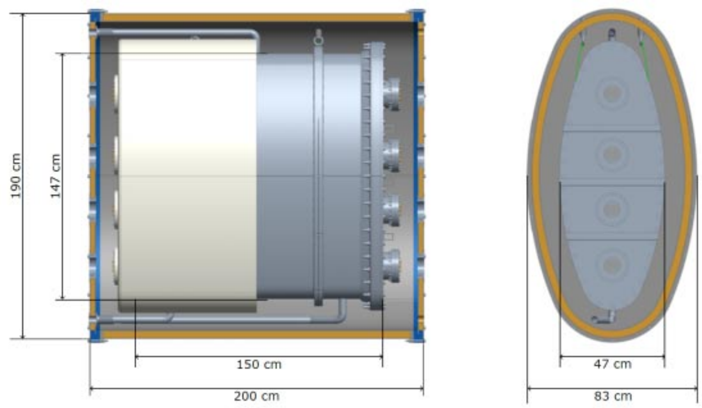

Fig. 2. – GRAIN rendering showing the inner and outer vessel with their dimensions, and the direction of the neutrino beam from LBNF. The inner vessel is made of stainless steel, while the outer vessel is made of carbon fiber and honeycomb in order to minimize the amount of material outside of the target.

The total number of events expected within GRAIN is typically 0.1 per spill, since most of the interactions occurs in the magnet yoke or in the ECAL, due to their large mass. In each spill GRAIN will hence observe charged particle tracks coming out from neutrino interactions within the SAND volume, and occasionally within the GRAIN volume or the immediate surroundings of SAND. In particular, a maximum number of 7 interactions are foresee to be detected in each spill, the average value being 1.5 interactions for spill. At the DUNE beam neutrino energy (up to 10 GeV) each neutrino interaction produces 2-3 tracks of primary particles, which, however, can further interact and produce secondary particles and showers. From each interaction the average number of tracks detectable in GRAIN (depositing more than 6 MeV) is 3.7, even if in some cases the number can be higher up to 40-60 tracks.

Such number of events cannot be managed with a traditional LArTPC because the drift time of the ionization charges is on the order of milliseconds and would result in event pile-up. A possible solution is to develop a novel tracking and calorimetry system entirely based on the imaging of LAr scintillation light. The idea behind this imaging system is the following: when charged particles cross the Liquid Argon, in addition to ionisation, part of their deposited energy excites Ar atoms inducing photon emission. By placing pixel-segmented photon detectors coupled to a focusing optic (which forms what we call a "camera") on the inner walls of the cryostat and immersed in Argon itself, it is possible to detect the emitted scintillation light ($\lambda = 127$ nm).

4·1. *GRAIN imaging system.* – Two technologies for the focusing optics are being evaluated, based on lenses and on coded aperture imaging, respectively. The first solution, show in fig. 3, consists of two plano-convex lenses of high purity non-crystalline fused silica glasses, transparent to VUV photons, separated by a gab filled with Nitrogen. The lens design provides optimal focus between 35 and 80 cm. Since for silica glasses the transmittance is acceptable for wavelengths bigger than 180 nm Xenon doping is necessary, reaching a wavelength of 175 nm.

The second approach is already well known in X-ray and gamma-ray astronomy but has been never used so far in particle physics experiments: the Coded Aperture Mask technique. In this approach, the scintillation light signal is filtered by coded aperture

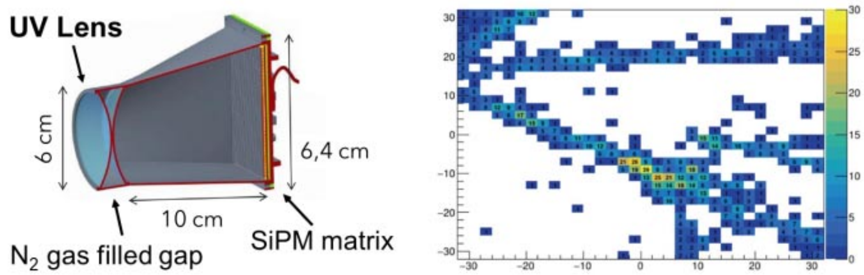

Fig. 3. – At left: lens based optical detector At right: example of a 2D image acquired by a lens-based camera

masks: slabs of opaque material with a certain number of holes, placed at a fixed distance in front of the photosensor. The pattern and size of the mask can be optimised to create a compact system, 2-5 cm thick, with a wide field of view (see fig. 4).

Both optical systems are intended to be coupled with a 1024-pixel SiPM array. Keeping the number of pixels fixed, different pixel areas are under study, namely 1×1 mm^2, 2×2 mm^2 and 3×3 mm^2. A notable drawback of SiPMs is their limited sensitivity to the 127 nm wavelength of Argon scintillation light. To address this problem, a wavelength-shifter may be needed. The solution could be either to dope Argon with Xenon (lens-based approach), or to coat the SiPM array surface with a wavelength shifter, like Tetra-Phenyl-Butadiene, which has an emission spectrum peaked at 430 nm (mask-based approach).

4·2. *Track reconstruction.* – In the case of the lens-based solution, the algorithm is divided in two different steps. The first is a 2D pattern recognition step, in which the raw images captured by the cameras are independently analysed to identify tracks, fit them, and compute their intersection points. Such 2D information are then matched across

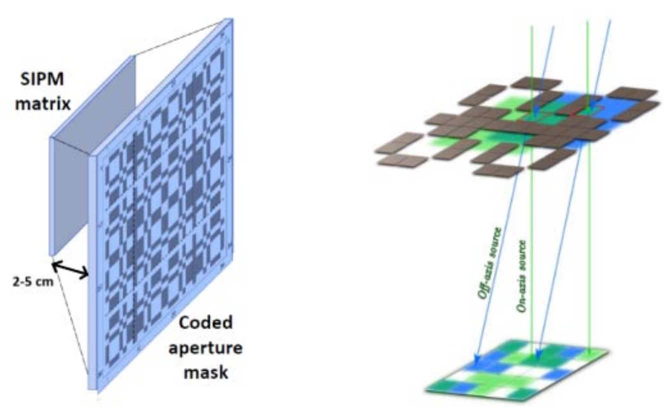

Fig. 4. – At left: coded aperture based optical detector. At right: the detector plane registers an overlapping set of multiple images, each set associated with one point source [8].

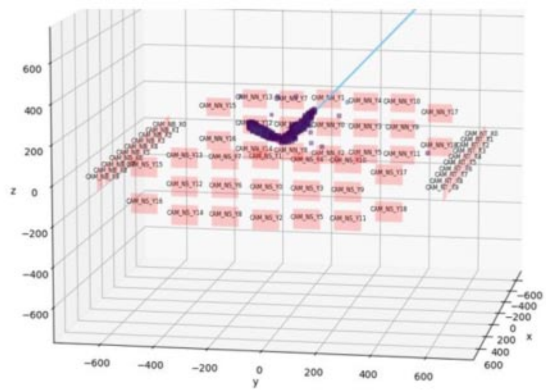

Fig. 5. – 3D reconstruction of a muon and proton track in a GRAIN-like geometry obtained with the ML-EM algorithm, in the case mask-based cameras. More information can be found in [8]

multiple views from different cameras, enabling the production of 3D reconstructed tracks and the localization of the interaction vertex. The second part of the reconstruction algorithm aims to recover the three-dimensional layout of the event, determining the position of the interaction vertex and the position and direction of the tracks in LAr [6].

In contrast to lens-based cameras, the 2D image detected by mask-based cameras is a convolution of multiple images projected from each hole of the mask. To retrieve the source image, various methods are available. The Maximum Likelihood Expectation Maximization (ML-EM) algorithm [7] is the primary technique under development for reconstructing tracks in GRAIN with mask-based cameras. This algorithm exploits an iterative approach to directly perform a 3D reconstruction of the images. The volume where particles propagate is segmented into voxels, and for each one of them, an emission probability is computed by projecting backward each photon detected by a camera through all possible mask holes. Combining projections from all cameras, the position of the light source is related to the voxels with the highest probability [8]. This technique is versatile and can work with various mask models and a low number of detected photons, but is computationally intensive, requiring a large number of operations for the reconstruction of a single event.

The results of this method are promising as visible in fig. 5, where the reconstruction of proton and muon tracks from a muon neutrino interaction in a GRAIN-like geometry is shown. More details on this technique can be found in [8].

4˙3. *Readout system.* – The exact number of cameras that will be required is not yet known, but an estimate of 50 ± 20 is realistic and is currently being studied. Having each camera at least 1024 channels, extracting the analog signal of each SiPM from the GRAIN cryostat is prohibitive. It is then assumed that the readout ASIC (Application-Specific Integrated Circuit) will be mounted in close proximity to the sensors, most likely on the opposite side of the same PCB, and will possibly have the same number of channels as the SiPM array.

5. – Conclusions

GRAIN is an important component of SAND and represents a unique innovation in the field of Liquid Argon detectors due to its optical readout. Two optical systems are currently being studied, one based on lenses and one based on Coded Aperture masks. Both offer their own set of advantages and drawbacks. Cameras based on lenses are better known, and provide a direct reconstructions of the source image. However, their usage in cryogenic environments is challenging and the high refractive index of liquid argon makes them have a limited field of view while also occupying a large volume. On the other hand, mask-based cameras are easier to build, have a larger Depth of Field, and boast a more compact design. Nevertheless, image reconstruction is nontrivial, as the image formed on the sensor turns out to be the convolution of images from each aperture, and requires complex reconstruction algorithms. The final configuration of GRAIN will be decided by looking at the reconstruction performance of both camera types in an upcoming prototype and could foresee a combination of lenses and masks to exploit the advantages each system provides.

REFERENCES

[1] Abed Abud A. *et al.*, *Snowmass Neutrino Frontier: DUNE Physics Summary*, arXiv:2203.06100 [hep-ex] (Mar. 2022).
[2] DUNE Collaboration, *JINST*, **15** (2020) T08009, arXiv:2002.03008.
[3] DUNE Collaboration, *Instruments*, **5** (2021) 31, arXiv:2103.13910.
[4] Adinolfi M. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **482** (2002) 364.
[5] Adinolfi M., Ambrosino F., Antonelli A. *et al.*., *Nucl. Instrum. Methods Phys. Res. A*, **482** (2002) 364.
[6] Vicenzi M., *A GRAIN of SAND for DUNE: Development of simulations and reconstruction algorithms for the liquid argon target of the SAND detector in DUNE*, PhD Thesis, Università di Genova (2023).
[7] Willingale R., Sims M. R. and Turner M. J. L., *Nucl. Instrum. Methods Phys. Res.*, **221** (1984) 60.
[8] Cicero V., *Study of the tracking performance of a liquid argon detector based on a novel optical imaging concept*, PhD Thesis, Alma Mater Studiorum - Università di Bologna (2023).