PROCEEDINGS OF SCIENCE

GRAIN: a novel liquid argon detector for imaging of neutrino interactions in the DUNE near detector

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1. Introduction

Since their discovery, neutrinos have captivated physicist worldwide, leading to a multitude of theories and experiments trying to unveil their mysterious nature. Despite extensive efforts, numerous open questions remain, and addressing one or more of these questions could profoundly impact our understanding of particle physics and the universe. Consequently, there is a strong motivation for developing new instruments, such as the Deep Underground Neutrino Experiment (DUNE) [1], which will employ innovative technologies and the most powerful available neutrino beam, to study the neutrino nature (among the other scientific objectives). To achieve these ambitious goals, studies towards the realization of advanced detectors are carried out. Among these the design and realization of an innovative Liquid Argon (LAr) detector is ongoing. The novelty of this detector is in exploring the possibility of performing an optical readout of the images, instead of the standard readout with drift electrons already exploited in previous and current experiments. Charged particles passing through liquid gases like LAr generate abundant scintillation light in the Vacuum Ultraviolet (VUV) spectrum, but conventional optics struggle in this range. Moreover, readout electronics must operate in cryogenic environments and detect single photons, necessitating the exploration of innovative techniques to address these challenges. This text will start with a brief description of the DUNE experiment and its scientific goals and will continue with the proposed solution for the optical readout of neutrino interactions in LAr and the preliminary results achieved.

2. The DUNE experiment and the Near Detector complex

The Deep Underground Neutrino Experiment (DUNE) is a new-generation long-baseline neutrino experiment with the main scientific goals of studying the neutrino mass ordering and the leptonic CP violating phase, along with the detection of astrophysical neutrinos and the search for physics beyond the Standard Model. DUNE will employ a high-power proton beam of 1.2 MW (upgradable to 2.4 MW) to produce neutrinos in the GeV energy range and will feature two experimental sites. The first site, denoted as Near Detector (ND) [2], will be located at Fermilab, at 575 m distance from the neutrino beam source. The second one, the Far Detector (FD) [3], will be placed at the SURF laboratory, 1300 km from Fermilab and 1500 m underground. A schematic view of the DUNE experiment is shown in Fig.1.

The FD will be composed of four Liquid Argon Time Projection Chamber (LArTPC) modules, of 17.5 kton each. Two modules (FD1 and FD2) will be installed during the so-called phase 1 of the experiment and they will be single-phase LArTPC with horizontal drift for FD1 and vertical drift for FD2. The other two modules will be instrumented during the phase 2 and their design has to be determined yet.

The ND complex will consist of three distinct large detectors with two of them capable of moving off the beam axis and one always placed on the beam direction. In Fig.2 the ND hall is presented in the configuration with three detectors on the beam axis (on the left) and with two detectors off axis (on the right). The two movable detectors are ND-LAr, a LArTPC employing the same detection principles of the FD, and ND-GAr, a gaseous Argon TPC that will be installed in the phase 2 of the experiment (the phase 1 will employ a Temporary Muon Spectrometer).

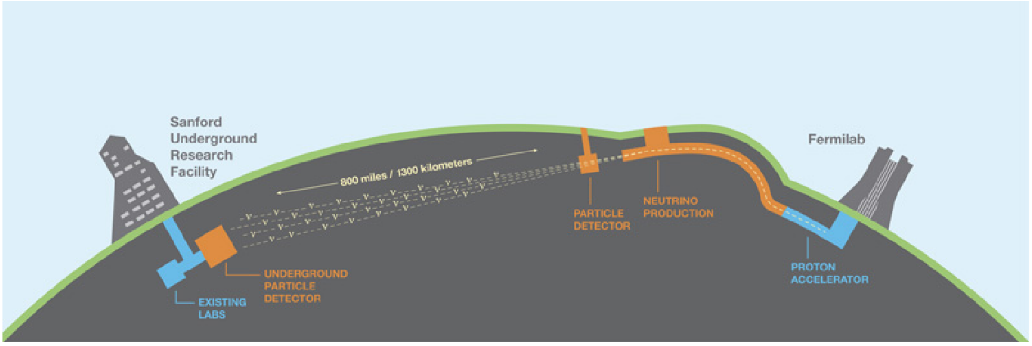

Figure 1: Representation of the DUNE experiment with the two laboratories. At Fermilab, in Chicago, the neutrino beam will be produced and the near detector will operate. At the SURF laboratory, in Sanford, located at 1300 km distance from the neutrino production point, the far detector will be installed [3].

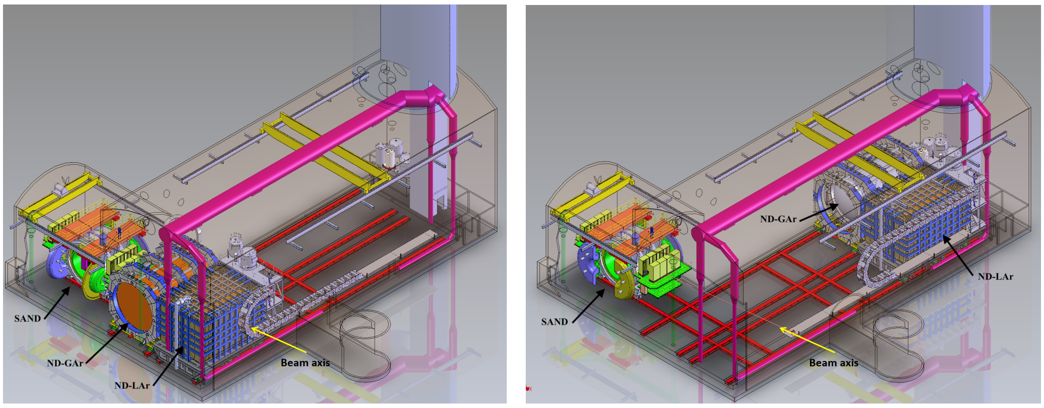

Figure 2: The DUNE near detector hall, at Fermilab. On the left, the three subdetectors (SAND, ND-GAr, and ND-LAr) are placed on the beam axis. On the right SAND is on the beam axis while the other two are in the off-axis configuration [2].

The latter will be fundamental to reconstruct muon momentum and charge for events not contained in ND-LAr and their off-axis movement will allow to scan over several neutrino energies.
The third component of the ND complex is the System for on-Axis Neutrino Detection (SAND). SAND will serve as an on-axis beam monitor and will have as its main goals the study of systematics uncertainties for the neutrino oscillation analysis, the measurement of neutrino cross-sections, and beyond standard model searches. It will be composed of a cylindrical magnet surrounding an electromagnetic calorimeter (ECAL) and by an inner volume. The latter will consist of a LAr active target (called GRAIN, GRanular Argon for Interactions of Neutrinos) and a tracker (STT). The SAND detector is shown in Fig.3 left where the outermost layers can be seen, with the calorimeter endcap open, and in Fig.3 right in section, with the various subdetectors.

3. GRAIN: the LAr active target in SAND

GRAIN will be placed upstream the neutrino beam, will have a mass of ~ 1 ton and will be composed of a cryostat (with an inner and an outer vessel) for an overall radiation length of ~ 1 X_0.

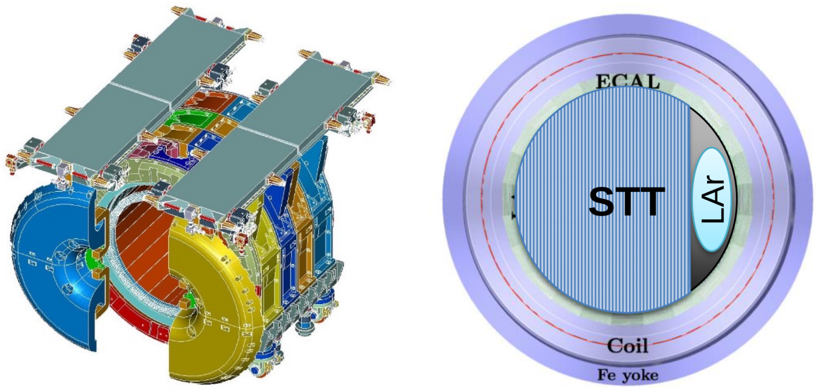

Figure 3: The SAND detector. On the left, the iron yoke, the coil, and the electromagnetic calorimeter, with the endcap open. On the right, the SAND view in section shows the various subdetectors (calorimeter, tracker, LAr active target) .

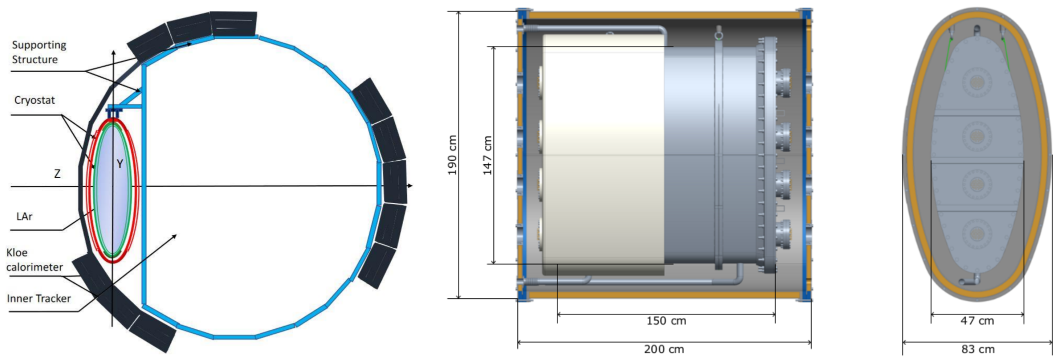

Figure 4: Layout of the GRAIN subdetector. On the left, the supporting structure, a part of the electromagnetic calorimeter, the cryostat and the LAr volume can be seen. On the right, the project of the inner and outer vessel of GRAIN.

The GRAIN detector can be seen in Fig.4 on the left placed in the SAND detector and on the right with its inner and outer vessels. The primary function of GRAIN is to detect the scintillation light generated by charged particles interacting in the liquid argon medium by using an optical system with nanosecond precision. By capturing and analyzing the scintillation light, GRAIN will identify and reconstruct the interaction vertex of neutrinos and the resulting particle tracks. This capability provides complementary measurements of tracks and energy to those obtained from the other SAND subdetectors (tracker and calorimeter) and will contribute to a more comprehensive understanding of neutrino interactions in liquid argon. To achieve this, the inner vessel will be instrumented with Vacuum UltraViolet cameras operating at LAr temperatures (87 K). Two distinct options are currently under investigation for the light readout: single-photon detectors, such as Silicon Photomultiplier (SiPM) arrays, coupled with UV gas-filled lenses or Coded Aperture Masks (CAMs). The two options under consideration are shown in Fig.5. On the left is the CAM option and on the right is the UV lens, both read by SiPM matrices.

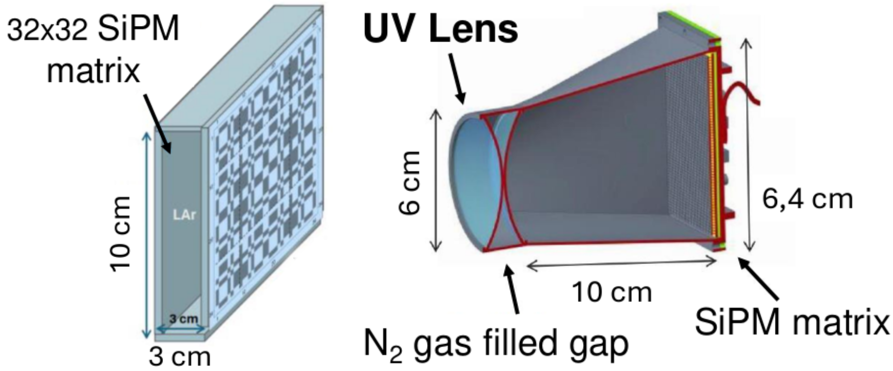

Figure 5: The readout options under study for the GRAIN detector. On the left the coded aperture masks and on the right the UV lens. Both of them are read by a SiPM matrix.

The lenses option has the advantage of providing a direct reconstruction of the source image but it's difficult to use in cryogenic environments. Moreover, the use of xenon doping is required to match wavelength and refractive index between LAr and lenses. Coded aperture masks consist of matrices of holes with specific locations and sizes (e.g. Hadamard masks) with the SiPM arrays on the focal plane. They have the advantage of being easier to build, more compact and with a larger depth of field, without necessarily requiring xenon doping. The drawback is the more complex reconstruction. The possibility of making 3-dimensional reconstructions with CAMs by using simple geometrical formulas has been investigated in [4]. Preliminary studies have been performed to validate the readout methods in GRAIN. These works are mainly based on analytical and statistical calculations along with simulations, showing evidence of the reliability of this type of measurement. Specifically, it was demonstrated that these new techniques could allow the detection of tracks over focal distances of tens of centimeters (instead of simple triggering signals) and recognize complex signals such as neutrino interactions. More general multiple views of Coded Masks and lenses are under consideration, in order to improve the quality of the reconstruction and refine the possibility of observations of the neutrino interaction vertices.

On the hardware side, fundamental activities are necessary to define the final detector design and characterize the proposed novel technologies. For this reason, a test facility comprising a tank filled with LAr and a system of lenses and masks read by SiPM arrays is being realized and installed at the University of Genova (Italy) and it is shown in Fig.6. The facility aims to test the proposed innovative technique of the optical readout in LAr and to compare the two techniques (lenses and CAMs). Specifically, the light collection in LAr will be studied by using a light source and the signal from cosmic rays using both lenses and masks coupled with SiPMs. Concerning the test with cosmic rays, a trigger made of plastic scintillator bars has been installed on the top and bottom of the tank. Moreover, the full-scale GRAIN detector is under design and preparation and will be installed at the INFN Legnaro National Laboratories (Italy).

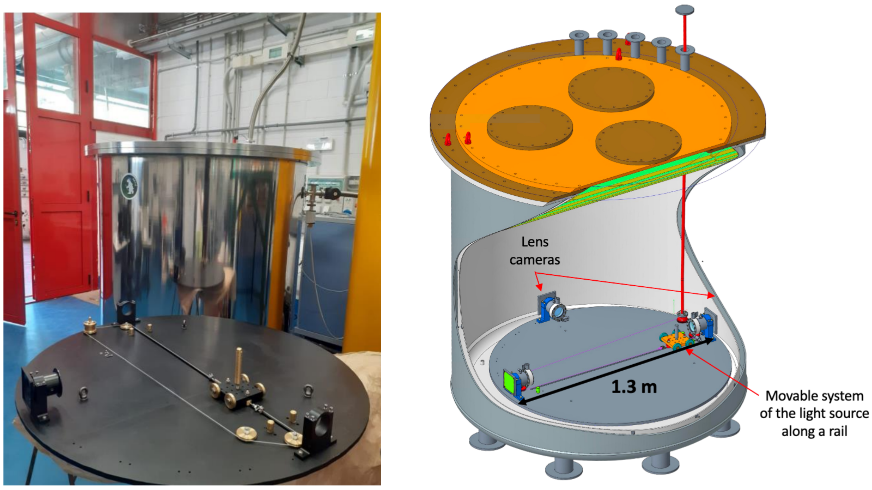

Figure 6: The test facility at the University of Genova on the left and a scheme showing the lenses and the light source on the right.

4. Summary and conclusion

The GRAIN detector will be part of the near detector complex of the future DUNE experiment. Given its task of reconstructing particle interactions in liquid argon by detecting the emitted scintillation light, the ambitious design and characterization of GRAIN pose significant challenges. Both hardware and software aspects of the GRAIN detector will be thoroughly studied, utilizing novel technological and computational techniques. These efforts aim to design a detector capable of handling the high event rate generated by the most powerful neutrino beam available at the time of installation. Moreover, they will pave the way for a new readout technique in liquid noble gases, which involves optical image readout. This innovation will profoundly impact physics experiments by enabling vertex, track, and energy reconstruction at the same time, by using detectors based on noble elements in the liquid phase.

References

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