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SAND - System for on-Axis Neutrino Detection - in the DUNE Near Detector complex

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The DUNE experiment aims to precisely measure the long baseline neutrino oscillation parameters. The DUNE Far Detector consists of four liquid Argon time-projection chambers (total LAr mass of 17 kton for each cryostat), that will be installed at the Sanford Underground Research Facility (SURF) in South Dakota, 1300 km from the proton beam target. The Near Detector complex, located at Fermilab, is fundamental for limiting the systematic uncertainties, due to the neutrino/antineutrino flux and to the cross-section. It comprises three complementary detectors: ND-Lar, ND-Gar and SAND (System for on-Axis Neutrino Detection). ND-Lar and ND-Gar can move off-axis, while SAND is the only detector permanently on-axis, whose primary goal is to monitor the beam and to measure the flux. In this talk, the SAND design and the expected performances will be described together with its role within the Near Detector complex for the DUNE physics program.

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[*] Speaker

1. The DUNE Experiment

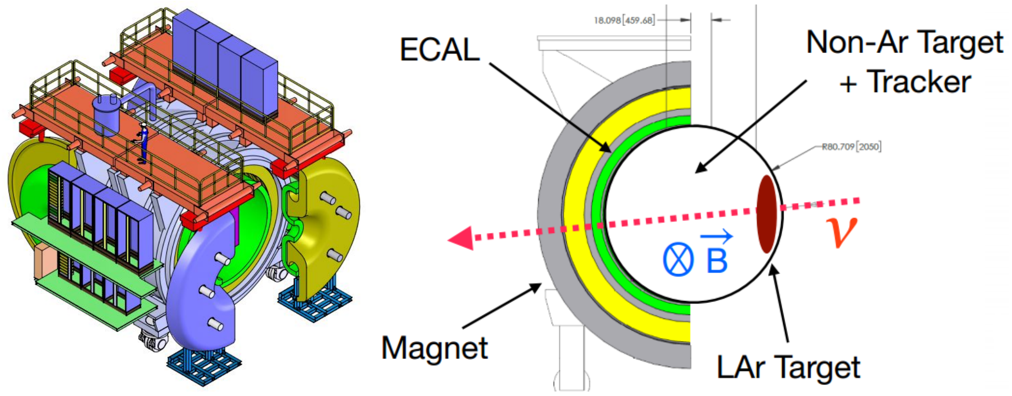
The Deep Underground Neutrino Experiment (DUNE) [1, 2] is a future long-baseline neutrino oscillation experiment whose primary goal is to achieve a percent level uncertainty in the measurements of neutrino oscillation parameters, allowing for an unambiguous determination of the neutrino mass hierarchy and the CP violating phase in the lepton sector. DUNE will consist of two underground detector complexes: the Near Detector (ND), hosted at Fermi National Accelerator Laboratory (FNAL) in Illinois, placed about 574 m away from the source of an high intensity neutrino beam, and the Far Detector (FD), hosted at Sanford Underground Research Facility (SURF) in South Dakota, for a total baseline of approximately 1300 km. The beamline is designed to provide a 1.2 MW neutrino beam (upgradable to 2.4 MW), with a wide energy range peaked at 2.5 GeV in order to access the first two oscillation maxima and several L/E ratios. The Far Detector will be a large liquid argon time-projection chamber (LArTPC) divided in 4 modules for a total mass of 68 ktons, while the Near Detector complex is going to be an integrated system of multiple detectors, in order to characterize and monitor the beam.

1.1 The Near Detector complex

The Near Detector complex is supposed to serve as the experiment's control, measuring and monitoring the beam, constraining the flux, and providing essential input for the neutrino interaction model. To achieve the precision required by DUNE's goals, the experiment must minimize systematic uncertainties and each component of the neutrino energy spectrum - namely, the cross-section, the flux, and the energy response - must be constrained independently with data in order to avoid relying on models. As a result, the Near Detector complex has been designed as a suite of three complementary detectors [3]: ND-LAr, a modular and optically segmented LArTPC (~300 tons), ND-GAr, a magnetized high-pressure GArTPC surrounded by a calorimeter, and SAND, a magnetized beam monitor consisting of an electromagnetic calorimeter, an inner target/tracker system and an active LAr target. While SAND is placed permanently on the neutrino beam, ND-LAr and ND-GAr can also move to take data in positions up to 30 m off the beam axis. This measurement program is known as DUNE-PRISM, exploiting the different energy spectra of the off-axis positions to sample the beam at different and narrower peak energies.

2. The SAND detector

SAND (System for on-Axis Neutrino Detection) is the permanently on-axis component of the Near Detector, placed downstream of ND-GAr and ND-LAr in a dedicated alcove of the ND hall. SAND consists of an inner tracker surrounded by an electromagnetic calorimeter inside a large solenoidal magnet. The superconducting coil and electromagnetic calorimeter (ECAL) are repurposed from the KLOE experiment, that previously operated at INFN-LNF (Frascati, Italy) to study ϕ-meson decays, while a new inner target/tracker system is being designed. A small LAr active target (GRAIN) is also foreseen in the upstream region of the internal magnetized volume. For reference, see Fig.1. The primary goal of SAND is to continuously monitor the stability of the beam and detect potential variations over time which could affect the oscillation analysis. This task is fulfilled mostly by the upstream part of the calorimeter and the inner tracker, allowing SAND



(a) SAND engineering model **(b)** Sketch of SAND vertical cross-section

Figure 1: Drawings of the current SAND design.

to be sensitive to changes in both the beam spectrum and profile within a week of data taking. In addition, SAND is capable of performing independent $\nu/\bar{\nu}$ flux and flavor content measurements, representing an important crosscheck for the other components of the Near Detector especially during the off-axis campaign. The inner tracker and the LAr target also provide a large sample of neutrino interactions on different nuclear targets (Ar, CH_2, C) which can be used to study interaction models and constrain nuclear effects. Moreover, the inner tracker design was developed to be able to incorporate neutrons in the event reconstruction, either in general or for selected event morphologies, in order to include regions of phase space in neutrino interactions not seen in previous experiments and improve the resolution on the energy transferred to the nucleus. Overall, SAND is designed to add robustness to the Near Detector against “unknown unknowns”.

2.1 Magnet and yoke

The solenoidal magnet was designed by Oxford Instruments to produce a uniform 0.6 T field over a 4.3 m long and 4.8 m diameter volume [4]. The nominal operating current is 2902 A and the stored energy is 14.3 MJ. The conductor is 10 mm by 5 mm composite consisting of a Rutherford NbTi cable co-extruded with high purity aluminium and wrapped with two half-lapped layers of 0.25 mm glass tape for insulation. The coil contains two layers of conductor, wound on flat, with a 1 mm high purity Al sheet between them. It is located in a cryostat, positioned inside an iron yoke, and cooled via liquid and gaseous He from a cryogenic service turret at the top of the yoke. The geometry of the return yoke is integral to the design in order to achieve good field uniformity and control the transverse field in the ECAL photomultiplier region.

2.2 EM Calorimeter

The electromagnetic calorimeter (ECAL) is a lead/scintillating-fiber sampling calorimeter, originally developed for the KLOE experiment. It is divided in a cylindrical barrel section, made of 24 trapezoidal 4.3 m long and 23 cm thick modules, and two endcaps, each with 32 differently-sized "C"-shaped modules. The barrel calorimeter modules are attached to the inner wall of the coil cryostat, while the endcaps are divided into two halves allowing access to the internal volume.

Once closed, the large overlap of barrel and endcaps modules leaves no inactive gap and guarantees a total 4π hermicity. All ECAL modules are made with approximately 400 alternating layers of grooved 0.5 mm lead foils and cladded 1 mm diameter scintillating fibers, glued together with a special epoxy compatible with the fiber. The fine-structure of the modules results in a uniform density of $5\,\mathrm{g/cm^3}$ and ~1.5 cm of radiation length. The overall thickness of the calorimeter is then ~ 15 radiation lengths. The fibers are grouped in cells and read on both sides of the module, using light guides and photomultipliers (PMTs). The position of the hit along the module is determined by the difference in the arrival times at each end, while the cell readout granularity defines the other two coordinates. The performance of the calorimeter was measured during KLOE operations and resulted in an excellent energy and timing resolution [5]:

$$\frac{\sigma_E}{E} = 5\%/\sqrt{E(\mathrm{GeV})} \qquad\qquad \sigma_t = 54\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})} \tag{1}$$

2.3 LAr target

A ~1 ton liquid Argon active target, will be placed upstream in the magnetized volume of SAND. GRAIN (GRanular Argon for Interaction of Neutrinos) will provide inclusive Ar interactions for the nuclear effect studies as well as a complementary Ar target permanently located on-axis for cross-calibration with the other detectors. The cryostat is under optimization and it is based on a C-composite material reinforced with an internal Al foil, resulting in a thickness of a small fraction of radiation length. The overall thickness of the LAr volume is kept to a minimum to reduce energy loss, showering and multiple scattering, as the outgoing particles will be analyzed by the downstream detector elements. GRAIN will be instrumented with an optical system for VUV scintillation light to localize and reconstruct the event in combination with the ECAL and the tracker. In addition to the basic timing and calorimetry capabilities of the optical readout, an R&D is in progress to develop an optical imaging system to spatially reconstruct the tracks. Two technologies are being evaluated, based either on lenses or coded aperture imaging [6].

2.4 Inner tracker

Two options were initially proposed for the inner tracker technology, one based on a combination of plastic scintillator cubes with TPCs (3DST+TPC option) and one based on straw-tubes (STT option). Both options satisfied the primary beam monitoring requirements and also provided additional hydrocarbon targets [3]. After an extensive review process, the straw-tubes tracker (STT) option was chosen by the collaboration as the final design.

3DST+TPC option This option included a three-dimensional projection scintillator tracker (3DST) as the main target, surrounded by three gaseous TPCs. The 3DST is a large 3D matrix of 1.5 cm plastic scintillator cubes, each optically isolated and read by three orthogonal WLS fibers. Its total active mass is 10.5 ton. The TPCs are filled with an optimized gas mixture and instrumented with a central cathode and two anodes planes of resistive MicroMegas for readout. The 3DST acts as a fully active target/tracker, providing a reduced threshold for protons (< 300 MeV) as well as calorimetric measurements of untracked low-momentum hadrons with short range. The momentum is reconstructed precisely by the TPCs for particles exiting the 3DST or by range for particle stopping inside. The high light-yield of the scintillator provides very good timing resolution (~ 0.5 ns). The

3D granularity and the timing resolution would also allow for an event-by-event neutron detection and kinetic energy measurement via time-of-flight.

STT option This option is based on a modular design involving orthogonal planes of straw tubes and thin target foils dispersed between them. The default STT module includes a target layer, a radiator layer and four 5 mm straw layers XXYY glued together, operated with a Xe/CO_2 or Ar/CO_2 gas mixture, which act as the tracking elements. The layout can be tuned by replacing or removing the target and/or the radiator layer. The current design assumes 78 default modules with CH_2 targets, 7 modules with graphite (C) targets and 5 tracking-only modules. Additional nuclear targets (Ca, Fe, Pb, . . .) could also be installed in future measurement campaigns. The average density of the full configuration is $0.18\,\mathrm{g/cm^3}$ ($\sim 1.3X_0$), for a total mass of 7.4 ton. The projected single-hit space resolution of a straw is $< 200\,\mu$m, in combination with a $\sim$ 1 ns timing resolution. The particle momenta can be reconstructed using transverse plane kinematics with a resolution of $< 3\%$, dominated by multiple scattering in the passive materials. The presence of radiators enhances the particle ID capabilities of the system via transition radiation, allowing good e/π separation. The STT design will also allow to extract ν-H samples by performing a model independent subtraction between CH_2 and C data with a kinematic analysis. Interactions on hydrogen are free from nuclear effects and the small energy transfer reduces the systematic uncertainties on the cross-sections, giving an additional handle for an accurate determination of the neutrino flux and the possibility of directly comparing data between H and heavier nuclei in the same detector.

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