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A drift chamber tracking system for SAND

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Summary. — The Near-Detector complex of the DUNE next-generation neutrino oscillation experiment will have the key roles of constraining systematic uncertainties in the oscillation measurements and carrying out an extensive program of precision searches. The SAND apparatus is one of the components of the Near Detector, tasked with monitoring the neutrino beam from an on-axis position and performing novel cross-section measurements on different target nuclei. The magnetized volume of SAND will host a low-density gas-detector tracker with thin (1–2% X_0) passive target layers of several materials, combining the large target mass (about 5 ton) and high spatial and momentum resolution optimal for performing neutrino interaction studies. A tracker based on large-area drift chambers is currently being developed as a backup solution for SAND. In this contribution, the role of this detector in SAND is presented, and the present status of the design, from the ongoing R&D activities on small-scale prototypes to its full integration in SAND, is discussed.

1. – SAND at the DUNE Near Detector

One of the three components of the DUNE Near-Detector complex (ND), the others being ND-LAr and TMS, SAND (System for On-Axis Neutrino Detection) will contribute to the key ND tasks of a) constraining the systematic uncertainties on the long-baseline oscillation analyses and b) conducting a wide range of precision measurements [1]. SAND will have a fixed on-axis position and will chiefly act as a beam monitor.

The design of SAND is based around the refurbished superconducting magnet (0.6 T) and electromagnetic calorimeter (ECAL) of the KLOE experiment. The KLOE ECAL has a sampling design with alternating lead/scintillating-fibre layers, with respectively $\sigma_E/E = 5\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 54/\sqrt{E(\mathrm{GeV})}$ ps energy and time resolutions [2]. In the upstream section of its magnetized volume, SAND will host the GRAIN liquid Argon active target (GRanular Argon for Interactions of Neutrinos), with a LAr mass of 1 ton.

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GRAIN will leverage a novel imaging system for LAr scintillation light, allowing for high spatial resolutions in the relatively high-intensity environment of the DUNE ND-complex [3]. The downstream portion of the SAND inner magnetized volume will be instrumented with the Straw Tube Tracker (STT), a gas-detector tracking system with diffuse C and CH_2 target layers, whose aims and design will be outlined in the remainder of this contribution.

2. – The physics program of STT

The diffuse C/CH_2 target design of STT will serve a crucial role in constraining the systematics on the neutrino flux measurement and nuclear smearing.

SAND will be capable of an accurate measurement of the absolute $\overset{(-)}{\nu}_\mu$ and relative $\overset{(-)}{\nu}_\mu$, $\overset{(-)}{\nu}_e$ fluxes. In STT, the energy dependence of the relative $\nu_\mu/\bar{\nu}_\mu$ flux can be determined at a sub-percent level after a 5 years exposure through the exclusive $\nu_\mu p \to \mu^- p\pi^+$, $\bar{\nu}_\mu p \to \mu^+ p\pi^-$ channels. The excellent resolution will enable STT to precisely locate the interaction vertex in the target layers and select a sample of interactions on H [4, 5].

The large statistics of nuclear-smearing–independent interactions on hydrogen in STT, will allow for an accurate measurement of ν-H cross-sections. Comparing such sample with the Ar interactions in GRAIN will then allow to directly constrain nuclear smearing on Ar, as the two detectors have a similar acceptance [4].

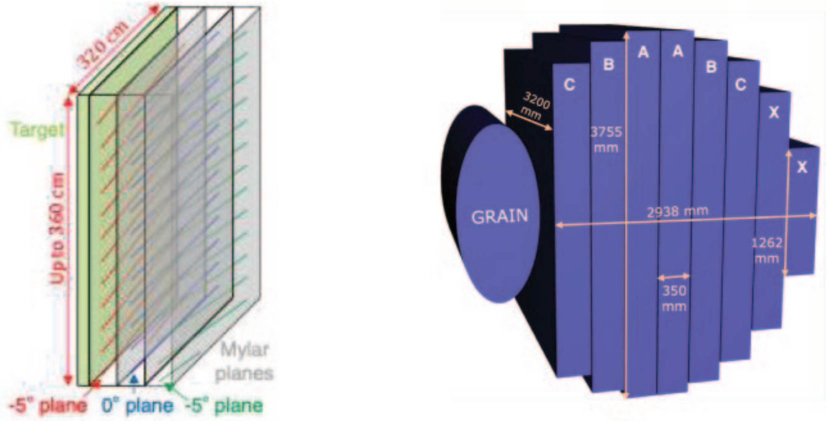
3. – The SAND Straw Tube Tracker (STT)

The SAND STT will respond to the twofold need of a large-enough target mass (~ 5 tons fiducial mass) and high spatial and momentum resolutions for neutrino cross-section measurements by way of its diffuse target design. The target mass is arranged in thin solid layers uniformly distributed throughout the tracking volume, accounting for more than 97% of the detector mass. Layers of low-mass straw-tube detectors (5 mm in diameter) are alternated to the target, ensuring high space ($< 200\mu$m) and momentum (*e.g.*, $\sigma(1/p)/(1/p) \simeq 4\%$ for 1 GeV μ) resolutions.

A majority of the modules will feature polypropylene (CH_2) targets, with layers of graphite (pure C) integrated in a fraction of the modules in place of CH_2 for the direct measurement of the C-background in the selection of hydrogen-interactions. The baseline configuration foresees 84 detector modules, for a total fiducial target mass of ~ 5 tons CH_2 and 0.6 tons of C. The total number of straw tubes is $\sim 2.2 \times 10^5$, with an average length of 3.2 m [4].

4. – A drift-chamber backup design for STT

The development of a backup design for STT has started, aiming at a reduced mechanical complexity and at a lower number of readout channels, while maintaining a comparable physics performance to the base solution. The backup design is based on large-area planar drift chambers, maintaining the modular layout of the straw-tube solution. Each detector module, pictured in fig. 1(a), will consist of a layer of target material (CH_2 or C) and three stereo-wire planes in a staggered $-5°$, $0°$ $+5°$ configuration with respect to the B-field axis. Stereo wires will reduce the left-right ambiguity while maintaining an optimal spatial resolution in the bending direction and minimising the number of channels read from the top and bottom sides of the module assemblies. Multiple detector modules will be placed inside a gas-tight frame, constituting a



(a) (b)

Fig. 1. – (a) Layout of a unit module of the drift chamber design. (b) Preliminary layout of the *super-modules* in the inner volume of SAND. Each *super-module* contains 9 CH_2 and a C target module.

super-module. A preliminary layout of the *super-modules* in the SAND inner volume is shown in fig. 1(b).

The wire planes consist of alternating anode sense wires (gold-plated tungsten, $d = 20\mu$m) and cathode field wires (copper-beryllium alloy, $d = 100\mu$m). Grounded mylar foils (20μm thick) are used to separate the wire planes. An Ar/CO_2 (85%/15%) mixture at an overpressure of ~ 5 mbar was chosen, as it was readily available for prototype development. A small-scale 3D model of the chamber was implemented with the Garfield++ toolkit [6] in order to optimize the cell configuration. A fast response simulation based on sampled induction signals from Garfield++ was then developed in order to characterise the cell.

4˙1. *Small-scale prototype.* – A small scale module prototype (30×30 cm^2) featuring three wire planes has been designed and built at the Bologna INFN section. Several runs with cosmic rays were conducted, allowing to test different voltage configurations and readout electronics and finally verify the Garfield++ response simulation results. The prototype was operated at $V_{field} = -1.5$ kV and $V_{sense} = +1.5$ kV respectively, as higher voltages led to discharges in the chamber. Particle tracking was performed with an already available scintillator-based tracker with ~ 1 mm resolution. The prototype cells were characterised in terms of their efficiency and wire distance to drift-time relation. Efficiencies $\gtrsim 90\%$ are reached for all instrumented wires, as shown in fig. 2(a).

4˙2. *Development of a medium-scale prototype.* – The construction of a medium-scale chamber prototype, with a 120×80 cm^2 active area, has started as of March 2025. The prototype will serve as a testbed for technical solutions to be applied to the full-scale detector, and its performance will be compared to that of a same-sized prototype of the STT base design. The prototype, a CAD model of which is shown in fig. 2(b), will correspond to a single chamber module. Smaller 1.4×1.2 cm^2 cells compared to the previous prototype will be used, for a total of 168 readout channels. Chamber readout will be based on the TIGER ASIC [7]. A run at a test beam is planned for the summer of 2025.

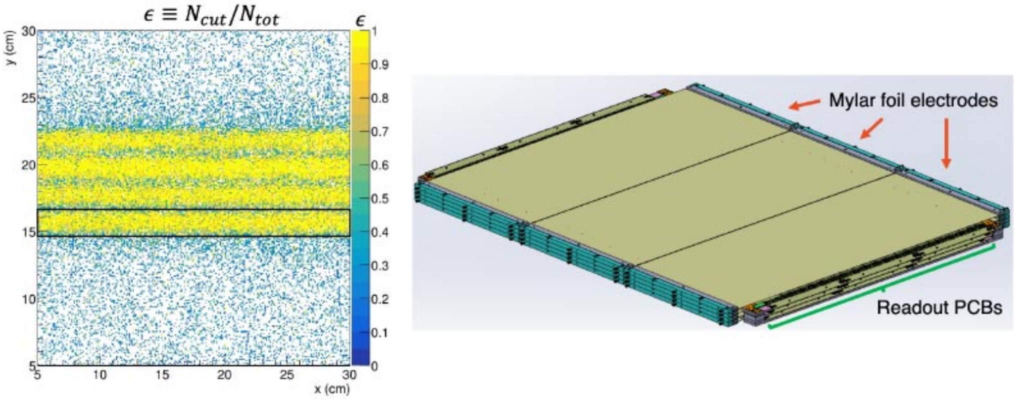


Fig. 2. – (a) Efficiency plot for a 30×30 cm^2 prototype wire plane, selecting signals with collected charge $> 3\cdot\sigma$ of the pedestal. Outlier points are due to noise or invalid track reconstruction. The outline of the cell is drawn in black. (b) CAD design of the 120×80 cm^2 prototype, showing the mylar foils and the readout PCBs.

5. – Prospects

The backup solution geometry has been implemented in the SAND simulation framework, and physics studies are ongoing with the aim of comparing the performance of the two solutions. The viability of the drift chamber design as a backup solution for STT will be evaluated over 2025, taking into account the performance of the medium-scale prototype at a test beam and the results of physics studies on the full scale detector in SAND. If proven consistent with the STT performance and to the broader SAND physics program, the design process of the full-scale modules is set to start.

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