The tracking system of SAND at the DUNE Near-Detector complex

A. Ruggeri(*)

INFN, Sezione di Bologna - Bologna, Italy
Dipartimento di Fisica e Astronomia, Università di Bologna - Bologna, Italy

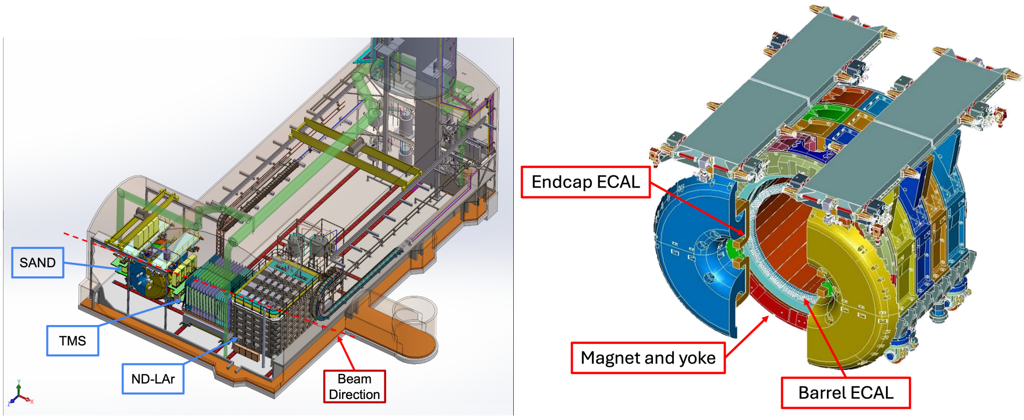
Summary. — The Near-Detector complex of the future DUNE neutrino oscillation experiment will enable precise oscillation measurements by constraining the relevant systematic uncertainties. Among the three components of the Near Detector complex, the SAND detector will monitor the neutrino beam from an on-axis position and carry out neutrino cross section measurements on several target nuclei. SAND will make use of a 0.6 T superconducting magnet and a lead-scintillator fibre electromagnetic calorimeter. In its inner magnetized volume, SAND will host a low-density tracker (STT) based on Straw Tubes and thin ($1-2\%$ X_0) passive target planes of different materials, combining a relatively large mass (~ 5 t) with high spatial and momentum resolutions. The use of alternating carbon and CH_2 targets in STT will provide a high-statistics $\nu(\bar{\nu})-$H CC ("solid hydrogen") interaction sample. This contribution will present the physics program of SAND and its tracker and discuss the present status of the design and analysis activities of STT.

1. – The DUNE Near Detector complex

The Near-Detector Complex (ND) of DUNE will fulfill two key roles in the experimental program: (a) it will measure the (anti)neutrino fluxes close (~ 600 m) to the beam source in order to constrain the systematic uncertainties affecting the long-baseline oscillation analyses, (b) it will carry out an extensive program of precision measurements and searches based on short-baseline neutrino physics [1].

In the first phase of DUNE operations, the ND complex will feature three detectors (shown in fig. 1a): ND-LAr, a modular LAr-TPC with a ~ 50 t fiducial mass, TMS, a magnetized steel-scintillator spectrometer and SAND, a magnetized beam monitor. ND-LAr and TMS will move off-axis to take data on different beam spectra, while SAND will have a fixed on-axis position. A magnetized high-pressure gaseous argon TPC (ND-GAr) will substitute TMS during the Phase-II of operation of DUNE [1].

(*) On behalf of the DUNE collaboration.



(a) (b)

Fig. 1.: (a) 3D view of the ND-complex detectors in the on-axis configuration, during Phase-I. (b) External view of SAND, showing the ECAL sections and the magnet coil. STT and GRAIN will be housed in the inner magnetized volume.

2. – The SAND detector

SAND (System for On-Axis Neutrino Detection) is based on the refurbished magnet and electromagnetic calorimeter of the KLOE experiment [2], instrumenting the inner magnetic volume with a LAr detector (GRAIN) and a low-density Straw Tube tracker (STT). Figure 1b illustrates the pre-existing electromagnetic calorimeter and magnet systems of KLOE.

2·1. *Magnet and EM-calorimeter*. – SAND will make use of the superconducting magnet of the KLOE experiment [3]. The system, in conjunction with its iron yoke, yields a 0.6 T field over a 4.3 m long, 4.8 m diameter volume. The KLOE electromagnetic calorimeter (ECAL) will be refurbished for use in SAND: it has a sampling design consisting of alternating lead/scintillating-fibre layers. The calorimeter system is composed of a cylindrical barrel section, located inside the magnet, and two endcaps. The average density of a module is 5 g/cm^3, for an overall calorimeter thickness of $\sim 15\,X_0$. During the commissioning and running phases of KLOE, the energy and time resolution of the ECAL were measured to be $\sigma_E/E = 5\%\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 54/\sqrt{E(\mathrm{GeV})}\,\mathrm{ps}$ respectively [3].

2·2. *The GRAIN LAr detector*. – The upstream section of the inner magnetized volume of SAND will be instrumented with the GRAIN liquid Argon detector (GRanular Argon for Interactions of Neutrinos), with a mass of ~ 1 ton. GRAIN will follow a novel approach for track reconstruction in LAr, based exclusively on the detection of the UV scintillation emission. The large light yield and fast emission time can be leveraged by fast and granular photon detectors to achieve high spatial resolutions in the relatively high-intensity environment of the DUNE ND-complex [4]. Two complementary optical systems are currently in development, utilizing respectively lenses and Coded Aperture Masks. Both systems will be coupled to SiPM-matrix light sensors [4, 5].

2˙3. *The STT system.* – The remaining section of the inner magnetized volume of SAND will host the Straw Tube Tracker (STT), a gas-detector tracking system with diffuse C and CH_2 target layers. The STT, which will be discussed in depth in sect. **4**, will be capable of high resolution measurements of neutrino interaction on multiple nuclear targets, including a high-statistics sample of $\nu - \mathrm{CC}$ interactions on hydrogen.

3. – The SAND physics program

From its fixed on-axis position, SAND will be capable of continuous and fast beam monitoring as well as carrying out a broader physics program of neutrino interaction measurements and precision searches.

3˙1. *Beam monitoring.* – A key aspect in the operation of DUNE ND will be the continuous monitoring of the $\nu_\mu/\bar{\nu}_\mu$-beam to detect potential variations which may affect the oscillation analysis. To this purpose, SAND will provide: (a) continuous measurements from a fixed on-axis position, (b) a large target mass (22.8 tons fiducial from the upstream ECAL), (c) an accurate reconstruction of the neutrino energy, (6% and 7% from ECAL and STT respectively), (d) measurements of the beam profile over a wide cross-sectional area. Such features will enable a sensitivity of $\Delta\chi^2 > 9$ in one week of data taking with 3.78×10^{19} POT (Protons On Target) for variations in most of the beam parameters [6].

3˙2. *Flux measurements.* – The precise knowledge of neutrino fluxes is crucial for both the primary Far Detector (FD) oscillation analysis and all other ND measurements. Specifically, it is necessary for unfolding the separate terms in the number of events for any exclusive process X either at ND or FD:

$$(1) \qquad N_X\left(E_{\mathrm{rec}}\right) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{\mathrm{osc}}(E_\nu) \sigma_X(E_\nu) R_{\mathrm{phys}}(E_\nu, E_{\mathrm{vis}}) R_{\mathrm{det}}(E_{\mathrm{vis}}, E_{\mathrm{rec}}),$$

where $\Phi(E_\nu)$ is the incoming (anti)neutrino flux, P_{osc} is the survival probability ($P_{\mathrm{osc}} \sim 1$ at ND), σ_X is the X process cross-section, R_{phys} is the response function introduced by nuclear smearing and R_{det} is the detector acceptance. SAND will be capable of an accurate determination of the absolute $\overset{(-)}{\nu}_\mu$ and relative $\overset{(-)}{\nu}_\mu$, $\overset{(-)}{\nu}_e$ fluxes through several complementary processes. In SAND, the energy dependence of the relative $\nu_\mu/\bar{\nu}_\mu$ flux can be determined at a sub-percent level with a 5 years exposure through the exclusive $\nu_\mu p \to \mu^- p \pi^+$, $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ channels on STT (see sect. **4**˙2) [6].

3˙3. *Constraints on nuclear smearing.* – Owing to its integration of the GRAIN Ar detector with the STT modules, SAND will be able to constrain the R_{phys} factor in eq. 1, as both systems have a similar acceptance R_{det}. The remaining $\sigma_X R_{\mathrm{phys}}$ is thus constrained by comparison between the Ar target and the lighter STT targets. To this end, the critical role is played by the hydrogen interaction sample in STT, for which $R_{\mathrm{phys}} \equiv 1$ (see sect. **4**˙2). Given the high expected statistics, the accurate measurement of σ_X on hydrogen is possible, so that the unfolding of E_ν only depends on R_{det} [6].

3˙4. *Background rejection.* – By applying a multivariate analysis of timing and topological information from both ECAL and STT, SAND will efficiently reject the background from beam-related neutrino interactions in the material surrounding the detector, reaching a rejection factor of 3×10^{-5} against CC+NC external interactions, with 92.7% efficiency and 99.6% purity [6].

3˙5. *Precision measurements and searches.* – Making use of its high available statistics and the accurate determination of the (anti)neutrino fluxes through $\overleftrightarrow{\nu}$–H interactions, SAND will be capable of exploiting the unique properties of the (anti)neutrino probe for the study of fundamental physics. A broad program of measurements and searches is planned, including precision measurements of the weak mixing angle ($\sin^2\theta_W$), isospin and strangeness physics, nucleon structure and QCD studies as well as searches for new physics [6].

4. – The SAND Straw Tube Tracker (STT)

4˙1. *Design.* – The SAND Straw Tube Tracker (STT) will satisfy the two-fold need for a large enough target mass ($\sim$ 5 tons fiducial mass) and for high space and momentum resolutions by way of its diffuse target design. The neutrino target mass is arranged in thin solid layers spread out uniformly throughout the tracking volume, accounting for more than 97% of the total detector mass. Layers of low-mass straw-tube detectors are alternated to the targets, providing high space ($<$ 200 µm) and momentum (*e.g.* $\sigma(1/p)/(1/p) \simeq 4\%$ for 1 GeV μ) resolutions thanks to their low density and high granularity. The use of dedicated target layers will guarantee the chemical purity of the materials and it will make it possible to change their configuration, in order to tune the average density of the detector ($5 \times 10^{-3} < \rho < 0.18$ g/cm^3) and perform measurements with several target materials.

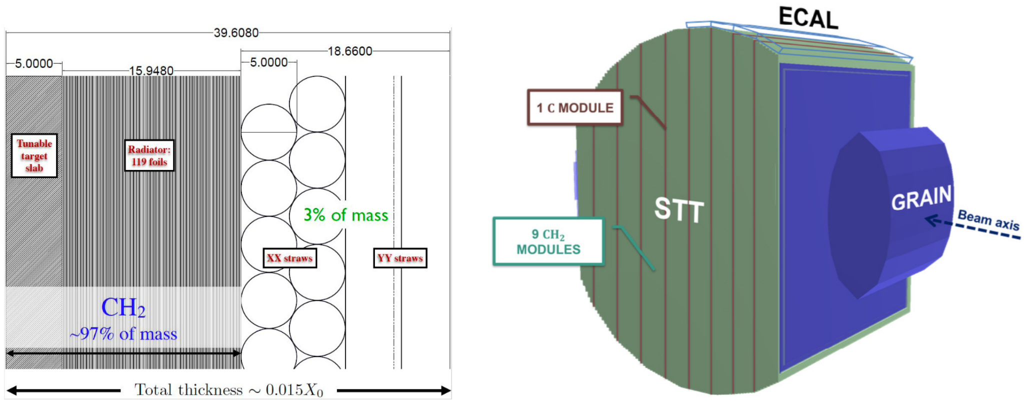
STT will be subdivided into independently operated and configured modules, for a flexible overall design. The default module configuration (in fig. 2a) aimed at ν-hydrogen interaction measurements, consists of: (a) a 5 mm thick polypropylene (CH_2) target slab, (b) a $\sim$ 14 mm thick CH_2 radiator for e/π separation via transition radiation, (c) four straw tube layers arranged in a XXYY configuration.

The straw tubes have 5 mm diameter, 12 µm mylar walls with Al coating and a 20 µm diameter gold-plated tungsten sense wire. The default gas mixture for the straws is Xe/CO_2 (70%/30%) gas mixture at 1.9 atm, ensuring sensitivity to the transition radiation as well as a relief to the mechanical tension applied to the supporting frames thanks to their overpressure.

The modular design of STT makes it possible to integrate various thin nuclear targets in place of the CH_2 radiator and target slabs. The main planned target material is graphite (pure C), for the direct measurement of the C-background in the selection of hydrogen interactions (see sect. **4**˙2). The baseline configuration, outlined in fig. 2b, foresees 8 C-target modules, 70 CH_2 modules and 6 target-less tracking modules (at the upstream and downstream ends), for a total CH_2 fiducial mass of $\sim$ 5 tons.

The ratio of C to CH_2 modules is tuned to optimize the purity of the H samples within technical constraints, leading to a ratio $M_{\mathrm{C}}/M_{\mathrm{CH_2}} \sim 0.1 - 0.2$ of the respective fiducial masses [7]. For the aforementioned CH_2 fiducial mass, this corresponds to $\sim$ 600 kg of graphite per $\sim$ 700 kg of H. The graphite modules are interspersed throughout the CH_2 modules, ensuring the same acceptance for both nuclear targets. In this configuration, the average density of STT is $\rho \sim 0.18$ g/cm^3 with a radiation length $X_0 \sim 2.6$ m. Each of the CH_2 and graphite modules corresponds to 1.5% and 2% of X_0 respectively [6].

While the default STT configuration is aimed at the measurement of $\overleftrightarrow{\nu} - H$ interactions, alternative nuclear targets are foreseen, including Ca, Fe and Pb.

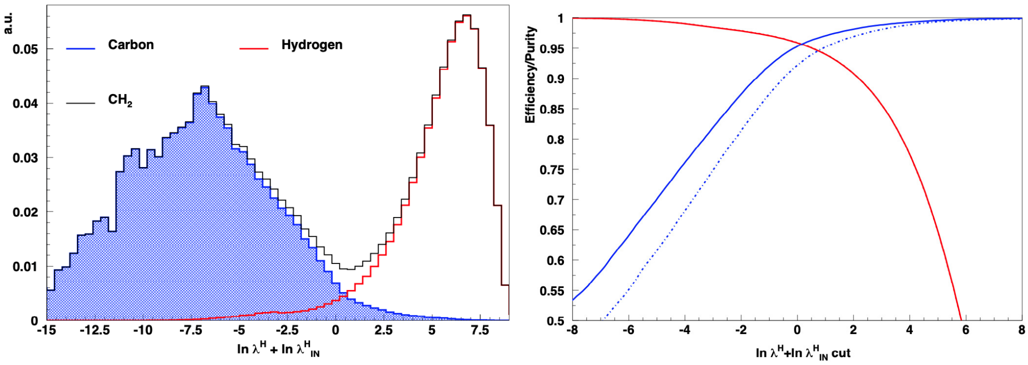


(a) (b)

Fig. 2.: (a) Cutaway view of a CH_2 STT module showing: (i) the tunable CH_2 target layer, (ii) radiator foils for e/π discrimination, (iii) four straw layers in a XXYY configuration. (b) 3D view of the SAND inner volume, with the upstream GRAIN LAr active target followed by STT. The barrel ECAL surrounds the inner volume.

4·2. *"Solid hydrogen" measurements.* – The study of (anti)neutrino scattering on hydrogen (*i.e.* free proton) which will be carried out by STT is crucial for the physics potential of the DUNE ND, as this one of the only two types of interactions to be free from nuclear effects (the other being ν-e elastic scattering) [6]. To this end, the C and CH_2 solid targets in STT overcome the technical issues related to solid or gaseous H-targets in underground experiments, hence the name *solid hydrogen* for this kind of analysis. The selection of H-events requires the excellent angular, momentum, vertex and timing resolutions of STT, to precisely locate the interaction vertex in the specific target layers. Kinematic selections on the corresponding event variables achieve a high rejection power. For the exclusive CC topology $\nu_\mu p \to \mu^- p \pi^+$, coming mainly from resonance production (resonances make up $\sim 68\%$ of ν-interactions in STT), the selection of H-interactions is performed through likelihood functions incorporating the complete event kinematics and the information from internal hadron system structure, respectively $\mathcal{L}^{\rm H}$ and $\mathcal{L}^{\rm H}_{\rm IN}$. The sum of the logarithms of the likelihood ratios between signal (H-event) and background (C-event), $\ln \lambda^{\rm H} + \ln \lambda^{\rm H}_{\rm IN}$ is the discriminant for the analysis, with the distribution shown in fig. 3a. The purity and efficiency as a function of the cut are given in fig. 3b for both $\nu_\mu p \to \mu^- p \pi^+$ and $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ samples [6, 7]. Table I shows the expected CC statistics in CH_2 and H in STT with the $\nu/\bar{\nu}$ beam modes and for the two planned beam power options (1.2 and 2.4 MW), assuming a 5 years data taking with each beam mode [8].

4·3. *Current status and prospects.* – The SAND STT is currently in the advanced development phase, with ongoing work on prototypes and on the design of the final modules. A medium scale (120×80 cm^2) STT module prototype was assembled at CERN over 2023 and has undergone successful testing with a ^{55}Fe source. Exposure at a muon testbeam is planned for 2024 and a further medium-scale prototype is in preparation. The design of the full-scale detector is ongoing, with studies underway on the gas and heat-exchange systems, the mechanical structure of the modules and target layers as well as on the assembly procedure. The selection of the production sites for the STT modules is furthermore being finalised.



(a) (b)

Fig. 3.: (a) Distribution of $\ln \lambda^{\mathrm{H}} + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$ for the H signal, C background and CH_2 (sum) for the $\mu^- p\pi^+$ CC topologies. The C and H distributions are normalized respectively to unit area and to the relative abundance in CH_2. (b) Efficiency (in red) and purity (in blue) as a function of the cut on $\ln \lambda^{\mathrm{H}} + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$ for the selection of $\nu_\mu p \to \mu^- p\pi^+$ (solid lines) and $\bar{\nu}_\mu p \to \mu^+ p\pi^-$ (dashed lines) on H from the CH_2 target.

Table I.: Expected CC statistics in STT (5 tons of CH_2) for interactions in CH_2 and H, with the different options considered for the DUNE (anti)neutrino beam [8].

1.2 MW beam statistics	CH_2	H
ν_μ-C (FHC, 5 yrs.)	35×10^6	3.6×10^6
ν_μ-C (RHC, 5 yrs.)	13×10^6	2.9×10^6
2.4 MW beam statistics	CH_2	H
ν_μ-C (FHC, 2 yrs.)	66×10^6	6.5×10^6
ν_μ-C (RHC, 2 yrs.)	24×10^6	4.3×10^6

REFERENCES

[1] V. Hewes *et al.*, "Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report," *Instruments*, vol. 5, no. 4, p. 31, 2021.
[2] L. Tortora *et al.*, "The KLOE detector and physics program," *Nuclear Physics B - Proceedings Supplements*, vol. 78, no. 1, pp. 157–162, 1999. Advanced Technology and Particle Physics.
[3] M. Adinolfi *et al.*, "The KLOE electromagnetic calorimeter," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 482, no. 1, pp. 364–386, 2002.

[4] M. Vicenzi, *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, Genoa U., 2023.

[5] V. Cicero, *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.

[6] G. Adamov *et al.*, “A proposal to enhance the DUNE Near-Detector complex,” 2021. DUNE doc 1362.

[7] H. Duyang, B. Guo, S. R. Mishra, and R. Petti, “A Novel Approach to Neutrino-Hydrogen Measurements,” 9 2018.

[8] R. Petti, “Precision Measurements of Fundamental Interactions with (Anti)Neutrinos,” in *27th International Workshop on Deep Inelastic Scattering and Related Subjects*, 10 2019.