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The System for on-Axis Neutrino Detection at the DUNE Near Detector complex

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The Deep Underground Neutrino Experiment Near Detector complex aims at constraining the systematic uncertainties and deconvolving the neutrino beam flux and cross-section models. The System for on-Axis Neutrino Detection (SAND) is the Near Detector component permanently on-axis. SAND is based on the 0.6 T superconducting magnet and electromagnetic calorimeter previously used in the KLOE experiment. The 40 m^3 magnetic volume will be filled with an active target/tracker system. One considered option foresees an upstream liquid Argon active target (about 1.5 t) and a Straw Tube Tracker (about 5 t). In this talk the design of SAND will be described and its performances discussed in view of the SAND primary goals, namely the beam monitoring and neutrino flux measurements.

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[*] Speaker

1. The SAND Detector

The SAND detector will reuse the existing superconducting magnet and electromagnetic calorimeter (ECAL) successfully operated at INFN-LNF for the KLOE experiment [1]. The internal magnetized (0.6 T) volume will be filled with a low-density and high-precision tracker based on the straw tube technology and a LAr-based tracker. The ECAL [1] is a 4π-hermeticity lead-scintillating fiber sampling calorimeter composed of a nearly cylindrical barrel, consisting of 24 trapezoidal cross-section modules, and two additional end-caps formed by 32 vertical modules placed laterally. The light read-out is performed by photomultipliers coupled with light guides resulting in a read-out sampling of about 4.5×4.5 cm^2. The energy and time resolutions, evaluated in running phases of KLOE experiment, amount to $5\%/\sqrt{E\,(\mathrm{GeV})}$ and $54/\sqrt{E\,(\mathrm{GeV})}$ ps, respectively [1].

The internal Straw Tube Tracker (STT) is composed of about 90 compact modules each with four (XXYY) staggered 5 mm-diameter straw tubes (hereafter straws) planes, where the Z axis is defined as the horizontal component of the beam direction, the Y axis is vertical and the X axis is defined requiring a right-handed coordinate system. The default module configuration foresees a 5 mm thick polypropylene (CH_2) target slab placed in front of the straws and a Transition Radiation (TR) radiator composed of 105 CH_2 foils 18 μm thick, inter-spaced by 117 μm air gaps placed between target and straws. The STT fiducial volume is defined by imposing a minimal distance of 20 cm from each ECAL surface and has a mass of 4.8 t, an average density of 0.18 g/cm^3.

The GRanular Argon for Interaction of Neutrinos (GRAIN) is placed upstream with respect to the STT and consists of an LAr-based detector, with a fiducial mass of about 1 t, aiming at exploiting the scintillation light to reconstruct neutrino interactions. Currently, the design of the cryostat is under optimization and several solutions for the light read-out are under study.

2. Event Simulation and Reconstruction

Two Monte Carlo simulation chains, one based on GENIE and GEANT4 and the other on FLUKA, have been setup. The LBNF neutrino flux for the CP-optimized beamline design has been used on the reported analyses. Custom C++ based software exploiting ROOT libraries is used for digitization and event reconstruction.

The digitization of the STT hits is performed applying a gaussian smearing of 0.2 mm and 1 ns to the position in the perpendicular plane and to the time of all hits above 250 eV threshold, while for what concerns the ECAL, the response (charge and time) of the photomultipliers, above the 2.5 photo-electrons threshold, is simulated taking into account the energy deposited in the active materials, the scintillator decay time, the photon propagation and light attenuation.

A first rough reconstruction of the neutrino interaction vertex position, (y_V, z_V), is performed on both views separately based on the transverse spatial spread profile of the STT digits. Subsequently, after the application of a conformal transformation $((y, z) \rightarrow (u, v))$ to the spatial coordinates of STT digits, tracks are identified as peaks in the distribution of the variable $\phi = (v/u)$ [2]. Finally a circular track model fit is applied and the particle momentum is estimated from the reconstructed curvature and dip angle. The obtained averaged resolution for the inverse total momentum, $\delta(1/p)/(1/p)$ for muons and electrons is 3.4% and 5% respectively.

The signals on both ends of ECAL cells allow to reconstruct time and longitudinal coordinate along

the cell. Adjacent digits are then grouped in clusters and their energy, time, position and direction are reconstructed. The energy and time resolutions thus evaluated agree with those measured by the KLOE Collaboration [1].
Muons and electrons are identified exploiting the ECAL information through a neural network and the TR radiator, respectively, while protons are identified exploiting the correlation between the range and the energy deposition in the STT. Neutrons from the neutrino interactions are identified as isolated energy deposits, with an efficiency of about 60% and their momentum reconstructed by the time-of-flight technique. The CC neutrino interactions are selected requiring an identified lepton track originating from the interaction vertex. The average resolution on the neutrino energy is about 6%. A fast reconstruction based upon the parameterized resolutions obtained by the full reconstruction has been implemented and used in these analyses.

3. Analyses

External Background Rejection Interactions in the magnet and ECAL can produce particles escaping into the inner tracker and interacting/decaying within the STT fiducial volume. These particles may represent a background source by mimicking the topology of a neutrino interaction in the fiducial volume.
At least 15 STT hits are required to reject this source of background. Then hits are grouped depending on whether their reconstructed position is in the innermost or outermost ECAL layer or in the STT fiducial volume or the STT veto region (i.e. the region complementary to the STT fiducial volume). The times of the earliest hits in these regions are used to define seven discriminant variables. In addition, three variables with topological information on the ECAL hits are used: *(i)* position of the earliest hit along the Z axis; *(ii)* difference between the number of hits in the upstream and downstream regions within a 20 ns window from the earliest STT hit; *(iii)* difference in the energy deposition between the outermost and innermost layers.
An artificial neural network (ANN) exploiting all ten variables is trained with a mixture of backgrounds and signal events. An ANN cut > 0.95 was applied as our main discriminant. To further improve the rejection power of the selection, the presence of at least one reconstructed track in the STT with a minimum of 4 hits in the YZ bending plane and a total reconstructed visible energy greater than 0.5 GeV is required. Overall a rejection factor of 3×10^5 against external background, a signal efficiency of 92.7% and a purity of 99.65% are obtained.

Beam Monitoring Since SAND will be the only component within the ND complex permanently located on the neutrino beam axis, one of its main tasks will be the continuous monitoring of the (anti)neutrino beam to detect potential variations over time which could affect the FD oscillation analysis. A list of potential variations of the beam parameters has been identified. The sensitivity to these variations on a weekly basis, corresponding to an average expected exposure of 3.78×10^{19} pot, was studied. Most of the sensitivity is provided by neutrino interactions in the upstream barrel ECAL with the momentum of the charged tracks being reconstructed in the STT. Neutrino interactions are selected requiring at least one reconstructed track with a minimum number of STT hits in the YZ bending plane. Then, for each variation of the beam parameters, a “varied” sample of neutrino interactions is obtained by re-weighting the “nominal” one using the ratio of the

Beam parameter	Nominal	Changed	Sensitivity (T)
Horn current	293 kA	296 kA	76.1
Water layer thickness	1 mm	1.5 mm	16.2
proton beam radius	2.7 mm	2.8 mm	27.6
proton target density	1.71 g/cm^3	1.74 g/cm^3	14.3
proton beam offset X	N/A	+0.45 mm	16.9
proton beam θ	N/A	0.07 mrad	0.2
Horn1 X shift	N/A	0.5 mm	10.7
Horn2 X shift	N/A	0.5 mm	0.2

Table 1: SAND sensitivity to the variations of the main beam parameters. The blue and red text colors indicate parameters characterized and not characterized by a cylindrical symmetry, respectively

corresponding three-dimensional beam profile (X, Y, E_ν) with respect to the nominal beam one. The distributions of the reconstructed neutrino energy, E_ν, for the “nominal” and “varied” samples are compared and the sensitivity is quantified with the test statistic:

$$T = \sum_{i=1}^{N} \frac{\left(N_i^{nom} - N_i^{var}\right)^2}{N_i^{nom}} \tag{1}$$

where the sum is over the total number of bins ($N = 80$), equally distributed in the 0−20 GeV energy range, while N_i^{nom} and N_i^{var} are the number of events in the i−th bin of the “nominal” and “varied” distribution, respectively. The variations of the beam parameters are divided into two categories, depending on whether or not they are characterized by a cylindrical symmetry with respect to the beam axis. For the former case a single E_ν distribution including contributions from all radial distances is considered. On the latter case, two separate E_ν spectra for the positive and negative values of X (or Y) are considered. Table 1 summarizes the sensitivity of SAND to the variations of the main beam parameters. A sensitivity $T > 9$ (roughly corresponding to 3σ) is achieved for most of the cases. Using an analysis scheme similar to the one described above, it was also shown that the SAND detector is able to detect, on a weekly basis, shifts in the beam direction down to 8.4 cm with a sensitivity $T > 9$.

Flux measurement The SAND detector is well suited for the determination of the absolute and relative neutrino flux. The relative ν_μ flux can be precisely determined by means of the interactions on H (free protons) which are free from nuclear smearing. The simplest topology available in ν_μ−H interactions is the process $\nu_\mu p \to \mu^- p \pi^+$. The impact of the systematic uncertainties due to the proton form factors, muon energy scale and the reconstructed hadronic energy has been studied and a selection on the energy transfer, $\nu < 0.5$ GeV has been considered in order to limit the effects of these uncertainties. The statistical and systematic uncertainties expected on the relative ν_μ flux will be below 2%. Similarly, the exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE process on hydrogen allows an accurate determination of the absolute and relative $\bar{\nu}_\mu$ flux, using the constraints $Q^2 \leq 0.05$ GeV^2 and $\nu <$ 0.25 GeV, respectively. Finally, the $\nu e \to \nu e$ elastic scattering offers a purely leptonic process with well understood cross-section to be used for the determination of absolute neutrino fluxes with an accurary better than 2%.

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