Snowmass2021 - Letter of Interest

3D-projection Scintillator Tracker (3DST) in SAND, a DUNE Near Detector Subsystem

(3DST is a detector proposed by the DUNE collaboration. However, this LOI is submitted by the signatories of this LOI not by the DUNE collaboration.)

S. Gokhale, S. Kettell, X. Qian, M. Yeh
Brookhaven National Laboratory, Upton, NY, USA

U. Kose, A. De Roeck
CERN European Organization for Nuclear Research, CH-1211 Genve 23, Switzerland

S. Gwon, C.H. Ha, K. Siyeon
Chung-Ang University, Seoul, South Korea

A. Bross, J. Freeman, A. Pla-Dalmau
Fermi National Accelerator Laboratory, Batavia, IL, USA

S. Bolognesi, A. Delbart, G. Eurin
IRFU, CEA Saclay, Gif-sur-Yvette, France

K. Dugas, J. Juneau, S.P. Kasetti, T. Kutter, S. Lin, M. Nauman, M. Tzanov
Louisiana State University, Baton Rouge, LA, USA

A. Tapia
Universidad de Medellín, Medellín, Colombia

A. Agarwal, P.S. Chong, M. D'Souza, D. Last, L. Lin, C. Mauger, M. Newcomer, R. Pellegrino, R. Van Berg
University of Pennsylvania, Philadelphia, PA, USA

V. Paolone
University of Pittsburgh, Pittsburgh, PA USA

H. Budd, T. Cai, R. Flight, S. Manly, K. McFarland, A. Olivier
University of Rochester, Rochester, NY, USA

D.A. Martinez Caicedo, J. Rodriguez Rondon, A. Sitraka
South Dakota School of Mines and Technology, Rapid City, SD, USA

C.K. Jung, C. McGrew, C. Riccio, A. Teklu, K. Wood, G. Yang, P. Zilberman
Stony Brook University, Stony Brook, NY, USA

Contact Information for corresponding author:
Chang Kee Jung (Stony Brook University) [chang.jung@stonybrook.edu]

NF Topical Groups: (check all that apply ☐/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF7) Applications
■ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (Other) *[Please specify frontier/topical group(s)]*
■ (IF6) Calorimetry

Abstract

The 3D-projection Scintillator Tracker (3DST) is proposed by the DUNE collaboration to be the fully active target/tracker in the System for on-Axis Neutrino Detection (SAND) detector which is one of the three subsystems in the near detector (ND) complex. The reference design of SAND consists of 3DST surrounded by low-mass tracking and an ECAL inside a large solenoidal magnet. 3DST will be composed of plastic scintillator cubes (1 cm^3), each with three orthogonal holes for WLS fibers for a 3D projectional readout of a neutrino event. The light from the WLS fibers will be read out by MPPCs and appropriate electronics. The total size of the 3DST is 2.53 x 2.36 x 2.04 m^3. SAND with 3DST will provide high statistics on-axis data that will enable us to make high precision neutrino beam monitoring, neutrino flux measurement and comprehensive neutrino-nucleus interaction studies. 3DST has a unique capability of event by event neutron detection and its kinetic energy measurement. The 3DST effort takes advantage of a synergy with the T2K Upgrade SuperFGD effort for shared technology and the resources. We propose a US contribution to 3DST as part of continuing US effort to prepare DUNE to meet the P5 requirements.

DUNE Near Detector Complex: The flagship physics goal of DUNE is discovery of CP violation in the lepton sector. In order to achieve this goal, it requires a highly capable near detector (ND) that can control the systematic uncertainties at an unprecedented (a few percent) level. In order to meet this challenging requirement, the DUNE ND is designed to comprise three subsystems (ND-LAr, ND-GAr and SAND) that are robust and complementary to each other, while each providing unique functions. In addition, the DUNE ND has the capability for two of those subsystems to move off the beam axis (DUNE-PRISM), providing a valuable extra degree of freedom in the ND data for oscillation analysis.

The ND-LAr will have a modular structure with pixel readout, but will not be magnetized. It will provide high statistics data on an argon target to be directly compared with the data from the DUNE far detector (FD). The ND-GAr will be magnetized so that it can separate charges, and will have an ECAL embedded. It will have a high resolution and low energy threshold allowing detailed studies of neutrino-Ar nucleus interaction modeling. Finally the SAND will provide high statistics on-axis data on a fully active scintillator target/tracker that will enable us to make high precision neutrino beam monitoring, neutrino flux measurement and comprehensive neutrino-nucleus interaction studies. These findings can then be compared to other studies using the vast amount of data taken by scintillator detectors around the world.

3D-projection Scitillator Tracker in SAND: The reference design of SAND consists of a massive plastic scintillator target surrounded by low-mass tracking and an ECAL inside a large solenoidal magnet. The plastic scintillator target is the 3D-projection scintillator tracker (3DST), which takes advantage of a synergy with the T2K Upgrade SuperFGD effort for shared technology and the resources. The technology was proposed in order to improve upon the deficiencies associated with the traditional planar detectors composed of scintillator bars while still utilizing a fully active target tracker that has calorimetric capability.

Each of 3DST's plastic scintillator cubes (1 cm^3) has three orthogonal holes of 1.5 mm diameter for 1.0 mm diameter Wave-Length-Shifting fibers (WLSs) for a 3D projectional readout of a neutrino event. The light from the WLS fibers will be read out by Multi-Pixel Photon Counters (MPPCs) and appropriate electronics. The scintillator cubes are covered by a $\sim$ 50 μm thick reflector that optically separates each cube[4]. The total size of the 3DST detector (current design) is 2.53 (width) x 2.36 (height) x 2.04 (depth) m^3. This novel geometry can provide a full angular coverage to any particle produced by neutrino interactions and reduce the momentum threshold for protons down to about 300 MeV/c (if at least three hits per view are required)[2]. Being a fully active detector, 3DST can also provide a calorimetric measurement of the energy deposited by low-momentum hadrons that are otherwise untracked due to short range.

3DST is surrounded by low-density tracking chambers that measure the charge and momentum of outgoing particles. The tracking chambers will be either normal pressure TPCs, straw tubes trackers, or a mix. The magnet and ECAL that surround the tracker are repurposed from the KLOE detector, which has a superconducting coil that provides a 0.6 T magnetic field and an excellent lead-scintillator ECAL[1].

Phyiscs Goals of 3DST/SAND: Unlike other "off-axis" long baseline neutrino oscillation experiments (NOvA, T2K and HyperK), DUNE utilizes on-axis wide-band beam and measures CP violation through distortions in the ν and $\bar{\nu}$ energy spectra in the FD. Thus, any undetected spectrum distortions originating from non-CP violation sources will bias the measurement. It is, therefore, imperative to have a detector that can monitor the variations in the beam spectrum in addition to the direction and width in a relatively short time scale (order of a week). While ND-LAr with its large size can fulfil this role, under the DUNE-PRISM scheme there needs to be a detector that monitors the beam at all times on-axis. 3DST/SAND with its large active target mass, along with the high precision ECAL, can meet this requirement. It should be noted that detectors at off-axis positions are less senstive to neutino spectrum changes and based on past experiences there are numerous scenarios of spectrum changes that cannot be detected by the beamline monitors.

SAND's requirement to measure the sign and momentum of muons makes it capable of similar measurements of charged hadrons. The target/tracking systems provide particle identification by dE/dx. The ECAL adds to the particle identification capability of the apparatus. These capabilities stem from the stringent beam monitoring requirements but allow SAND to conduct a comprehensive neutrino interaction measurement program that augments DUNE's oscillation physics mission.

Event-by-event Neutron Kinetic Energy Measurement: One extraordinary capability of 3DST/SAND is event by event neutron detection and its kinetic energy measurement via ToF utilizing the 3D fine granularity and the sub-ns timing resolution. This allows a nearly full reconstruction of a charged current event with greatly reduced missing energy, which has never been achieved before. This capability provides a new tool for studying neutrino interactions. It will help reduce systematic uncertainties associated with the hardon energy that is now one of the dominating uncertainties in the oscillation analysis. It will allow us to perform detailed studies of neutrino-nucleus interaction models and to measure $\bar{\nu}$ flux with a greater precision[3].

Neutron Beam Test at LANSCE/LANL: Motivated by the possibility of measuring the kinetic energy of neutrons from neutrino interactions on an event by event basis, neutron beam test data was collected with two different prototypes to characterize the detector response to neutrons and measure the neutron cross section on SuperFGD/3DST scintillator. A total of 20 days of data was taken in December 2019. The LANSCE neutron beam has kinetic energies up to 800 MeV. We recently received a beam time approval of our second neutron beam test run at LANSCE in fall 2020.

Global Synergy, Strategy and Collaboration: Besides the neutron beam test, a charged beam test was performed with the SuperFGD prototype in 2018 at CERN. The SuperFGD detector is being built at this time and will be completed in spring 2022. T2K with its upgraded ND detector including SuperFGD will take data beginning fall 2022 and until the start of Hyper-Kamiokande. Thus, it will accumulate high statistics data at the neutrino energy ($\sim$ 600MeV) that is very close to the 2nd oscillation peak ($\sim$ 700MeV) in DUNE. SuperFGD is a de facto working prototype of 3DST and will provide invaluable neutrino beam data for understanding detector responses as well as for studies of neutrino interaction modeling. The majority of the US institutions involved in 3DST are also members of the SuperFGD group, resulting in an effective usage of resources and knowledge/expertise transfer. Groups from Asia, Europe and Latin America are currently participating in the 3DST effort or have interests in joining the effort in the near future.

Detector R&D: One of the anticipated challenges we will face when constructing 3DST is manufacturing and assembling nearly 11 million scintillator cubes. Although the production and assembly method developed for SuperFGD works fine and is manageable, since the number of cubes needed for 3DST is almost six times larger than that of SuperFGD, it would be desirable to develop a process that is less complex, labor intensive, risky, and yet is cost effective. A process that could possibly achieve all of these aspects is 3D-printing. If we were to able to produce 3DST "super-cubes" by 3D-printing, it would avoid a rather complicated and labor intensive production and assembly process. Thus, R&D efforts in this direction have been commenced within the 3DST group in recent years. In order to achieve the 3D-printing of 3DST, the following two major advances must be made: (1) the development of a 3D printable plastic resin with scillating characterstics similar to the current plastic scintillator used for SuperFGD, and (2) the identification and/or development of a 3D printer that is capable of using two separate resins to print optically separated scitillator cubes. When successful, the 3D printing manufacturing technology for plastic scintillators will have a far reaching applications, ranging from particle physics detectors to medical devices.

Another substantial improvement in the construction process can be achieved by producing scintillator cubes using injection moulding that creates three althogonal holes in the process of moulding. This will eliminate the need for drilling three holes separately after the moulding as it is done currently, which is a labor intensive process. Other scintillator R&Ds to improve the scintillator quality is also on going.

Education and Training: As can be seen from the author list, many junior faculty/staff scientists, postdocs, grad students and undergrad students have been participating in the 3DST detector design and physics studies; prototype construction; neutron beam test data taking and analysis; and detector R&D.

Conclusion: We propose a US contribution to 3DST as part of continuing US effort to prepare DUNE to meet the P5 requirements.

References

[1] M Adinolfi et al. The KLOE electromagnetic calorimeter. *Nucl. Instrum. Meth. A*, 482:364–386, 2002.

[2] A. Blondel et al. A fully active fine grained detector with three readout views. *JINST*, 13(02):P02006, 2018.

[3] L. Munteanu, S. Suvorov, S. Dolan, D. Sgalaberna, S. Bolognesi, S. Manly, G. Yang, C. Giganti, K. Iwamoto, and C. Jesús-Valls. New method for an improved antineutrino energy reconstruction with charged-current interactions in next-generation detectors. *Phys. Rev. D*, 101(9):092003, 2020.

[4] John Nugent. The upgrade of the T2K Near Detector ND280. *PoS*, NuFact2019:118, 2020.