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A Novel Highly Segmented Neutrino Detector: The Super Fine Grained Detector for the Upgraded T2K ND280 Near Detector

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The T2K neutrino experiment in Japan obtained a first indication of CP violation in neutrino oscillations. To obtain better sensitivity, T2K upgraded the near detector. A novel 3D highly granular scintillator detector called SuperFGD of a mass of about 2 tons will be functioning as a fully-active neutrino target and a 4π detector of charged particles from neutrino interactions. It consists of about two millions of 1 cm^3 optically-isolated plastic scintillator cubes. Each cube is read out in three orthogonal directions with wave-length shifting fibers coupled to compact photosensors, micro pixel photon counters (MPPCs). SuperFGD was installed into the ND280 magnet and exposed to the neutrino beam since October 2023. In this presentation, the main detector parameters, detection of first neutrino events, and its performance in the neutrino beam are described.

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1. The T2K Experiment and Motivation for SuperFGD

The primary objectives of ongoing and future long-baseline neutrino oscillation experiments are to search for CP violation, determine neutrino mass ordering, and measure neutrino oscillation parameters precisely. The Tokai-to-Kamioka (T2K) experiment [1] uses a neutrino beam from the Japan Proton Accelerator Research Complex (J-PARC) directed towards the Super-Kamiokande detector, located 295 km away. The ND280 near detector, positioned 280 m from the hadron production target, measures the properties of the neutrino beam prior to oscillations, aiding in the assessment of unoscillated neutrino spectra and reducing systematic uncertainties related to neutrino flux, interaction cross-section, and detector acceptance.

ND280's design includes several components, such as the UA1 magnet, Pi-Zero detector (POD), time projection chambers (TPCs), fine-grained scintillator detectors (FGDs), an electromagnetic calorimeter (Ecal), and a side muon range detector (SMRD). It has effectively reduced uncertainties in oscillation measurements, but it faces limitations in tracking efficiency, particularly for particles at high scattering angles and low momentum.

To address these challenges, an upgrade of ND280 has been built and integrated into ND280 (shown in Fig. 1) to improve detection efficiency for high-angle and low-momentum particles, accumulate more ν_e interactions, and enable neutron detection.

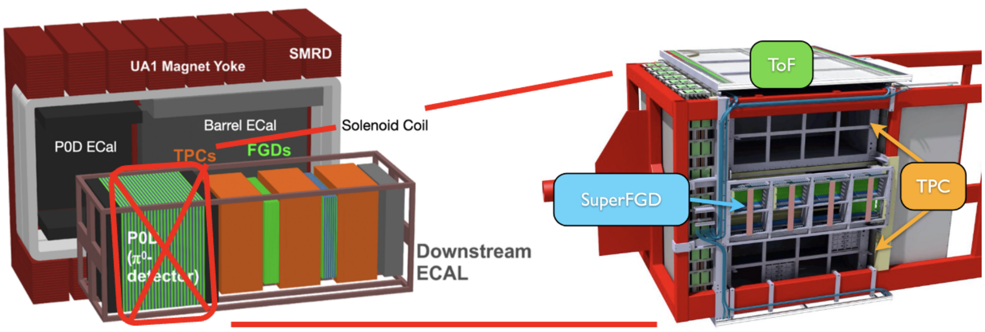

Figure 1: The T2K near detector ND280 before the upgrade (left) and after upgrade (right).

The upgraded detector features:

- Full polar angle acceptance for muons with comparable momentum resolution and charge measurement to the current ND280.
- High tracking efficiency for low-energy pions and protons to ascertain event topology.
- An efficient Time-Of-Flight detector for reconstructing track directions.
- Enhanced neutron detection and kinetic energy measurement capabilities.

The upgrade involves a fine-grained fully-active plastic scintillator detector, named SuperFGD [2] , which will serve as both the target for neutrino interactions and the detector for track reconstruction around the interaction vertex.

2. SuperFGD Hardware Components

SuperFGD is a two-meter-long plastic-scintillator detector that serves as an active neutrino target. It comprises a two-tonne polystyrene-based detector segmented into $1 \times 1 \times 1$ cm^3 optically isolated cubes. When a charged particle, such as a muon or an electron, passes through a cube, it produces scintillation light, which depends on the particle's energy and the distance traveled in the scintillator. To minimize light leakage between adjacent cubes, each cube is covered with a white diffuser obtained through chemical etching. Wavelength-shifting (WLS) optical fibers capture and convey the light to multi-pixel photon counters (MPPCs) for photon counting. In total, 1,956,864 sensitive elements are read out by 55,888 electronic channels. Figure 2 shows a model of SuperFGD and scintillator cubes with inserted WLS fibers. The innovative 3D cubic geometry

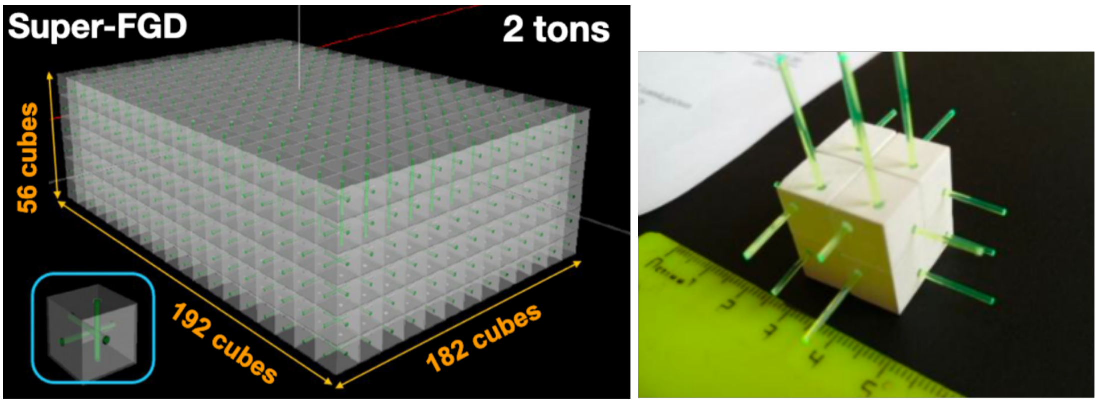

Figure 2: SuperFGD model (left) and scintillator cubes with inserted WLS fiber (right).

of SuperFGD provides isotropic particle tracking, resulting in improved particle tracking, enhanced angular acceptance and lower momentum threshold for detection. Additionally, the cubic geometry increases the scintillation light output by nearly a factor of four compared to current ND280 scintillator detectors. The detector is homogeneous, constructed entirely of plastic (predominantly polystyrene), which is crucial for precise measurements of neutrino cross-sections. This design improves upon traditional plastic-scintillator detectors that utilize long scintillator bars instead of fine-granularity cubes.

Assembly, Enclosure and Installation: The scintillator cubes, produced at UNIPLAST Co. in Vladimir, Russia, utilize a composition of optical quality polystyrene doped with 1.5% paraterphenyl (PTP) and 0.01% POPOP, and are fabricated through injection molding. Following production, the cubes receive a reflecting layer through etching, resulting in a white micropore deposit that enhances diffuse reflectivity, with an average thickness of 50-80 μm. Drilling of three orthogonal holes of 1.5 mm diameter accommodates 1 mm diameter WLS fibers, necessitating a high production rate of over 4,000 cubes per day, managed by multiple drilling machines and operators. The mean weight of the cubes was measured to be 99.81 g per 100 cubes, with systematic errors largely influenced by the precision of the weighing equipment. Cube sizes exhibited minor fluctuations, with measurements revealing average dimensions of approximately 10.16 mm and variations attributed to the thickness of the reflector and manufacturing inconsistencies. Quality checks were performed to ensure proper alignment and sizing during pre-assembly, with cubes assembled into a 3D array ready for further testing, confirming the alignment necessary for fiber insertion. Overall, the final weight of the scintillator cubes in the SuperFGD was estimated at 1953.1±1.0 kg, with careful measurement of cube dimensions and hole positions to maintain quality control throughout the production and assembly processes.

The mechanical box must support the substantial weight of 1,956,864 plastic scintillator cubes and 55,888 WLS fibers while ensuring precise coupling with MPPCs and an LED calibration system. It is designed to withstand stresses from installation and potential earthquakes without interfering with other detectors. Constructed from carbon fiber and rigid foam, the box features a complex internal structure that minimizes gaps between cubes to prevent fiber breakage, while maintaining tight tolerances for optimal light yield and alignment during operation.

The installation of the scintillator cubes at J-PARC, Japan, occurred from October 2022 to April 2023, following a structured assembly process that involved sealing the mechanical box, stacking and aligning pre-assembled cube layers, and subsequently installing WLS fibers, MPPC-PCBs, and calibration systems. A specialized support and top access system facilitated this process, allowing precise alignment and assembly of the detector components. After testing and ensuring proper alignment during installation, all fibers and readout cables were attached, followed by light shielding to prevent interference from ambient light, culminating in functionality tests for the complete setup.

MPPCs: The SuperFGD employs Multi-Pixel Photon Counters (MPPCs) from Hamamatsu Photonics, specifically the S13360-1325PE model, which offers improved sensitivity and lower noise compared to previous models. Each MPPC has a 1.3 mm x 1.3 mm sensitive area and 2668 pixels, optimizing photon collection from the attached wavelength-shifting (WLS) fibers. The system uses Y-11(200) WLS fibers, known for their established performance, with a total length of nearly 70 km, designed to efficiently transport scintillation light to the MPPCs. Quality assurance procedures ensure high performance across all components, including precise alignment and functionality testing of the MPPCs and fibers.

Electronics: The digitization of MPPC analog signals in the Super-FGD detector is managed by specialized readout electronics organized in 16 crates, each containing 14 Front-End Boards (FEBs) and one Optical Concentrator Board (OCB). The FEBs utilize CITIROC chips to handle 256 channels, processing signals through programmable preamplification and shaping, before sending data to the OCB via a dedicated backplane. Each channel has a low and a high gain pre-amplifier and following a fast shaper provides signal timing information including time over threshold (ToT) information. The OCB consolidates data from the FEBs and communicates with a Data Acquisition (DAQ) system, facilitating both data collection and configuration commands. The entire system operates under a synchronized clock managed by a Master Clock Board (MCB), ensuring precise timing and event detection across all FEBs. Various tests have been conducted to evaluate the FEB's linearity, electronics cross-talk, and overall performance in the context of the experimental setup.

The combination of MPPCs and electronics provide sub-ns timing and a large dynamic range which are critical for neutron time of flight reconstruction and to measure charge particles ranging from minimum ionizing particles to stopping protons, respectively.

DAQ and Calibration: The CPU running Linux on the OCB operates the MIDAS frontend, which processes data from the FPGA and sends it to a backend PC that assembles events from multiple OCBs and the MCB into a global DAQ. To enhance event processing, the system incorporates histogramming for LED calibration, centralized FEB configuration management, and robust error detection, while also supporting various trigger types and operating modes for cosmic events.

The LED calibration system is designed to quickly check detector response during commissioning, calibrate gains during operation, and monitor long-term stability, utilizing a Light Guide Plate (LGP) for light distribution in a compact setup. The system features advanced components, including an array of blue LEDs, notched LGPs, and a custom LED driver that generates precise light pulses, all integrated into a black acrylic container to minimize light leakage. Quality control measures ensure uniformity and optical performance by using a mass evaluation system with CMOS cameras to inspect thousands of notches for light intensity before installation.

The fully assembled, tested and installed SuperFGD is shown in Fig. 3 (left) in between two horizontal TPCs. A sample neutrino candidate event in SuperFGD and its surrounding ND280

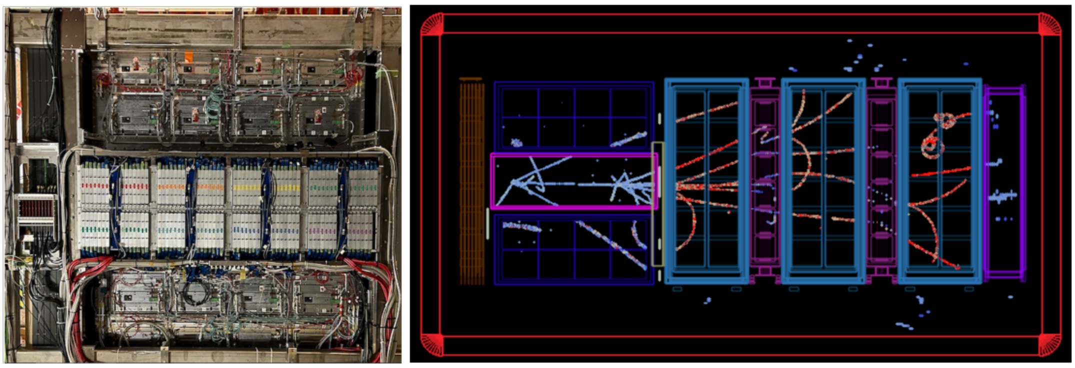

Figure 3: SuperFGD installed in between two horizontal TPCs (left) and neutrino candidate event in ND280 upgrade (right).

sub-detectors is displayed in Fig. 3 (right) where the neutrino beam enters from the left. Backward and large angle tracks in SuperFGD can be seen clearly.

3. SuperFGD Performance

Evaluating the overall performance of the SuperFGD detector is crucial for precise particle detection and neutrino interaction reconstruction, focusing on metrics such as light yield, WLS fiber attenuation, time resolution, and MPPC calibration stability. Calibrations are conducted utilizing LED light transmitted via a light-guiding panel to WLS fibers that direct the light to the MPPCs. This process enables the monitoring of gain stability, with MPPCs registering signals of 1 to 10 photoelectrons, ensuring consistent calibration throughout the experiment.

Light yield measures the scintillation light produced by charged particles and is a key performance metric. It is assessed using cosmic muon tracks, focusing on specific angles to ensure accurate results. For a single cube and a single fiber a mean light yield of about 25 photo electrons (p.e.) has been measured. Cosmic and neutrino beam data are also used to verify the relation between low and high gain electronics channels as well as between high gain and time over threshold (ToT) readout.

WLS fiber attenuation length: The 3D position information of particle tracks in SuperFGD provides light yield information as function of distance from the MPPCs. A cosmic data set is used to extract the WLS fiber attenuation length by fitting an exponential function which accounts for a short and a long attenuation component to the data. Results obtained to date indicate good agreement with manufacturer specifications for the WLS fibers used.

Time resolution is critical for event reconstruction, and corrections for the time walk effect are applied to refine timing accuracy based on signal amplitude. The overall time resolution is then measured using hit distributions from the detector, integrating findings from light yield and time corrections to enhance the detector's capability for capturing and reconstructing particle interactions effectively. In a study using mip signals in single cubes and considering signals in both horizontal fibers, each requiring a minimum signal size of 40 p.e., a preliminary time resolution of about 1.1 ns has been measured.

4. Summary and Outlook

The T2K experiment requires reduced systematic uncertainties for more sensitive measurements of neutrino oscillation parameters. The highly granular SuperFGD along with the other ND280 upgrade detector offers full phase space coverage, lower energy threshold and neutron detection capabilities. The SuperFGD was commissioned and began taking cosmic muon and neutrino beam data in November 2023 and May/June 2024. Quantitative performance characterizations of the SuperFGD are currently in progress, focusing on light yield measurements, linearity of response, WLS fiber attenuation measurements and timing resolution. Upcoming tasks include the measurement of dE/dx and use of the Bragg peak for proton identification, electron/gamma separation, and neutron studies.

References

[1] Abe, K. et al. (T2K Collaboration), The T2K Experiment, Nucl. Instrum. Meth., A659, 2011, p.106-135

[2] Abe, K. et al. (T2K Collaboration), T2K ND280 Upgrade - Technical Design Report, 2019 , arXiv: physics.ins-det/1901.03750, CERN-SPSC-2019-001 (SPSC-TDR-006)