The SuperFGD for the T2K near detector upgrade

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Abstract. Tokai-to-Kamioka (T2K) experiment is a long baseline neutrino experiment in Japan. T2K started data taking in 2010 and obtained a hint on matter-antimatter asymmetry in neutrino oscillations. To provide better sensitivity, T2K plans to have a run extension with higher intensity beam and an upgrade of the T2K near detector. We adopted a novel detector called SuperFGD as an upgraded fully-active target tracker. It consists of about two millions of plastic scintillator cubes and about sixty-thousand readouts through WLS fibers and MPPCs. It provides fine granularity and larger acceptance to suppress systematic error. The new detector will be ready to accept the beam in 2022. Here we report the current status of the new detector.

1. Introduction
With the main goal of observing CP violation at the 3σ level, a project was launched in 2017 to upgrade one of T2K’s near detectors, the ND280. The new design for the ND280 includes a highly granular scintillator detector based on a novel idea to use 1×1×1 cm³ cubes read out along three orthogonal directions by wavelength-shifting fibers. This detector, named the SuperFine-Grained Detector (SuperFGD), is the subject of this paper.

The T2K experiment has two near detectors 280 m away from the target point that study the neutrino beam before oscillation, INGRID (Interactive Neutrino GRID) and ND280. While INGRID is along the beam line, ND280 is placed 2.5 degrees off-axis. The main objectives of the ND280 are to measure the flux, flavor content and energy spectrum of the neutrino beam, and help study neutrino-nucleus interactions.

The current design for the ND280 is shown in figure 1. The two Fine Grained Detectors (FGDs) act as the neutrino interaction targets with a combined mass of 2 tons. The upstream FGD1 consists of 30 layers of extruded scintillator bars that alternate in vertical and horizontal orientations in the plane perpendicular to the beam. On the other hand, FGD2 is made of six 3 cm thick layers of water sandwiched between seven scintillator layers. Three Time Projection Chambers (TPCs) sandwich the FGDs to detect and track any emerging charged particles [1].

While the current design provides excellent efficiency in the forward region, the efficiency suffers significantly for scattering angles larger than 40 degrees. It also has limited capabilities in tracking short-ranged particles and backward tracks.

To address these weaknesses, an upgrade project for the ND280 was launched in February 2017. The upgraded detector design aims to increase the acceptance and the efficiency, achieve better identification of track directions, double the target mass for neutrino interactions from 2 to 4 tons. Thus, significantly increase statistics. It also aims to improve tracking low energy hadrons around the neutrino interaction vertex.
The chosen configuration for the ND280 upgrade is shown in figure 2. Modifications were introduced to the upstream part, while the current ND280 tracker remains unchanged. Since the P0D has already realized its measurements and is limited by systematics, it is removed from the upgraded ND280 and replaced by three new detectors. A high granularity scintillator detector of a large mass (SuperFGD), two high-angle time projection chambers (HA-TPCs), as well as a set of time-of-flight counters.

The two HA-TPCs are designed based on the existing TPCs with similar features and capabilities. They will be able to provide 3D track reconstruction, as well as charge and momentum measurements for high-angle tracks originating from the new scintillator detector. TPCs are also well suited to track low momentum tracks as those produced in neutrino interactions [2].

Sandwiched between the two HA-TPCs is the new scintillator detector which acts both as the target for neutrino interactions as well as the detector to reconstruct the tracks around the interaction vertex. SuperFGD has a large mass of about 2 tons and a size of $192 \times 184 \times 56$ cm$^3$ [3].

Finally, the Time-of-Flight (TOF) counters are used to determine the direction of the tracks by measuring the crossing time of charged particles compared with the timing information provided by the SuperFGD. This measurement will make it possible to separate neutrino interactions occurring within the detector from any external background, it will also potentially improve particle identification.

In order to evaluate the performance of the new ND280 compared to the current design, a selection of $\nu_\mu$ Charged-Current (CC) interactions has been developed using simulations. For each interaction, the most energetic negative track is selected as the muon candidate. The event is then retained if the muon candidate crosses one of the TPCs active volumes for more than 20 cm and if it is identified as a muon according to the particle identification (PID) algorithms. High angle tracks are also added if the muon candidate enters the ECal and is identified as a muon there [2].

Figure 3 shows the distribution of the muon true momentum versus the polar angle for the selected events for the current and upgraded ND280 designs. According to these figures, the new design clearly shows an improved acceptance for high angle and backward tracks.

The new detector components of the upgraded ND280 are currently under construction. The detector is planned to run in 2022.
Figure 3. Distribution of selected $\nu_\mu$ CC events as a function of true muon momentum and polar angle for the current (a) and upgraded (b) ND280 [2].

2. The SuperFGD Design

The SuperFine-Grained Detector is the active target for neutrino interactions in the upgraded ND280 detector. It is a plastic scintillator detector composed of a large number of optically independent $1\times1\times1$ cm$^3$ cubes read out along three orthogonal directions by wavelength-shifting fibers (WLS fibers), see figure 4. The SuperFGD is a fully-active detector with isotropic acceptance, its fine granularity, along with its quasi 3D readout, allows for reconstructing short tracks around the interaction vertex [2].

Figure 4. Sketches of the SuperFGD detector showing its full dimensions, and a cube with the optical fibers passing through.

The building blocks of the SuperFGD are the scintillating cubes. The 1 cm cubes are made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP [2]. To reduce the amount of light leaking from the cubes, they are coated with a 100 $\mu$m thick (on average) chemical reflector by etching their surface with a chemical agent creating a white micropore deposit over the polystyrene. The SuperFGD will require about 2 million cubes.

The cubes are produced by Uniplast in Vladimir, Russia. Sets of 12 cubes are created by injection molding, they are then coated with the chemical reflector before they are individually drilled three orthogonal 1.5 mm diameter holes to accommodate the 1 mm diameter WLS fibers. Each fiber is read out on one end by a Multi-Pixel Photon Counter (MPPC) connected through an optical interface. The SuperFGD will be using the Y-11(200)MS WLS fibers produced by
Kuraray, and the S13360-1325PE Hamamatsu MPPCs\cite{2}.

Compared to the current FGDs, the SuperFGD has the advantage of providing 3D readout for each 1 cm$^3$ of the detector volume. Figure 5 shows a sketch of an FGD and a particle track. Each layer of bars can provide information on two of the three coordinates of the interaction point. Therefore, in order to be able to locate the track, it has to cross a minimum of two layers of bars in the FGD. The FGD is further limited when several tracks are produced, in which case the deposited energy cannot be uniquely identified and assigned to a particular spatial direction.

![Figure 5](image1.png)  \hspace{1cm}  ![Figure 6](image2.png)

**Figure 5.** Tracking in the current FGDs. A distance is introduced between the two layers of bars for clarity.

**Figure 6.** Tracking in the SuperFGD. The rest of the fibers along the Z direction are not drawn for clarity.

On the other hand, figure 6 shows a sketch of one layer of cubes in the SuperFGD. If an interaction occurs in one of the cubes, the energy deposition is read out by three orthogonal fibers providing the three coordinates of that cube. Each of these fibers would provide two of the three coordinates, hence the term *quasi*-3D. By combining these three sets of coordinates, the cube where the interaction occurred can be located. This fine granularity is what allows for the detection of short tracks around the neutrino interaction vertex.

3. Detector Assembly

After production, the cubes are sent to INR (Moscow) for pre-assembly. Figure 7 shows the steps of cube assembly. Strings of cubes are pre-assembled using fishing lines of 1.3 mm diameter. These strings are then sewn together to create 2D arrays of cubes. The planes of 2D arrays are then stacked to obtain the 3D detector.

Once the whole volume is pre-assembled, the fishing lines are replaced by the WLS fibers one by one. Finally, the optical interface and readout electronics are connected.

The fishing line method provides the flexibility to align and assemble the large arrays of cubes despite the small variation in cube sizes and hole positions.
4. Readout Electronics

The readout electronics system of the SuperFGD is based on the CITIROC (Cherenkov Imaging Telescope Integrated Readout Chip) used by the Baby-MIND detector of the WAGASCI experiment [4]. The main component in this scheme is the Front End Board (FEB) which houses four CITIROC chips. Each CITIROC chip contains 32 channels that correspond to 32 MPPCs.

A common high voltage is applied externally to all MPPCs, but can be modified for individual MPPCs using the Digital-to-Analogue converter (DAC) each CITIROC chip is equipped with. Each MPPC signal goes through two voltage-sensitive pre-amplifiers with different gain (high gain (HG) and low gain (LG)) that ensure the detection of charges from 160 fC to 320 pC.

Along with the CITIROC chips, each FEB is equipped with a 12-bit, 8-channel Analogue-to-Digital converter (ADC) to digitize the analogue HG and LG signals from the CITIROC, an FPGA Altera Aria X to control and manage the timing and data flow from the CITIROCs and the ADC, and an optical link to transmit the data to a data acquisition system.

Because of the multiplexing and digitization stages, the analogue signals from the HG and LG lines suffer from a dead time of 9 $\mu$s. On the other hand, the digital signal with the timing information is continuously sampled by the FPGA at a rate of 400 MHz. This proves useful when two signals occur on one fiber within a time period less than the dead time. In this case, the time difference between the rising and falling edge (known as the Time-over-Threshold, ToT) can be used to obtain the amplitude of the signal. Thus, the SuperFGD electronics provide three signal outputs for the amplitude; HG, LG and ToT.

5. Prototype Beam Tests

Two SuperFGD prototypes were built and tested at CERN using a charged particle beam. The first was a small $5 \times 5 \times 5$ cm$^3$ prototype [5] in 2017, and the second was a larger $24 \times 48 \times 8$ cm$^3$ in 2018 [6]. The latter was also tested at the Los Alamos National Lab in late 2019.

The prototype construction helped improve the detector assembly procedure, and the beam tests provided preliminary insights on the capabilities and performance of the detector.

Figure 8 shows an event display from the CERN beam test. The three projected displays represent the front, top and side views respectively. The event shows a photon interaction producing an $e^-e^+$ pair that diverge under the applied magnetic field of 0.2 T. This demonstrates the capacity of the SuperFGD to resolve tracks emerging from the interaction vertex.

Several studies were conducted on both prototypes, more thoroughly on the second (larger) one. According to these studies, the SuperFGD exhibits excellent performance.

The response of the SuperFGD to minimum ionizing particles (MIPs) was studied using a muon beam of 2 GeV/c momentum. Figure 9 shows the mean light yield for 384 readout channels as a response to a MIP with an average light yield of 50.16 p.e./MIP/fiber. The three signal outputs of the electronics show good agreement, indicating an efficient calibration procedure. In this plot, “PE” represents the optimal signal path for each hit such that MPPC saturation
Figure 8. An event display from the CERN beam test on the $24 \times 48 \times 8 \text{cm}^3$ prototype showing a photon conversion to a pair of $e^- e^+$.  

Figure 9. Mean light yield for 384 readout channels connected to 24 cm fibers, showing the three signal outputs of the electronics [6].

Figure 10. $dE/dx$ curves for stopping proton samples comparing the beam test data to simulations [6].

effects are avoided and the ToT signal is used when the HG and LG are unavailable.

Using the fraction of protons in CERN’s hadron beam, a sample of 0.8 GeV stopping protons was selected. A stopping proton event is characterized by the large energy deposition towards the end of the proton track. Figure 10 shows the $dE/dx$ curves of the beam test stopping proton sample compared to simulations of the SuperFGD, the two samples show good agreement with around 450 p.e. deposition at the stopping point. In both cases, a few points with non-zero energy deposition appear following the stopping point. The statistics in this region are very scarce, as shown by the large error bars, and are believed to be the result of interactions at the end of the track that cause scatterings or release secondaries.

The channel resolution of the SuperFGD was also investigated using straight muon tracks with 2 GeV/$c$ momentum. A reference time was chosen for each event, and the time difference between each hit and the reference was computed. Once plotted in a histogram, the standard deviation of the Gaussian fit was taken to be the combined time resolutions of the time reference and the channel. Assuming equal time resolutions, the standard deviation was divided by $\sqrt{2}$ to obtain the channel time resolution. Figure 11 shows the distribution of channel resolution for 812 channels in the prototype, with an average of $1.14 \pm 0.06 \text{ ns}$.

Finally, although PID is not one of the primary tasks of the SuperFGD, the prototype shows good PID capabilities using the $dE/dx$ and range of particles. Figure 12 shows the average $dE/dx$ for protons and muons/pions, where clear separation can be observed.
6. Conclusion

The SuperFGD is the new active target for the ND280 upgrade. It is currently under construction, and as of September 28th 2020 over 83% of the final detector layers were assembled using fishing lines. This addition will significantly enhance the performance of the ND280 by increasing the number of statistics and improving the detection of short ranged particles.

Two prototypes were built and tested using the charged particle beam at CERN. The results show an average energy deposition of 50.16 p.e./MIP/fiber and a channel time resolution of 1.14 ± 0.06 ns. They also show promising PID capabilities.

The full detector will be ready for data taking in 2022.

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