Fine-Grained neutrino detector for the T2K neutrino oscillation experiment

Kei Ieki, Akira Murakami,
on behalf of the T2K collaboration

Kyoto University

Abstract

T2K is a long baseline neutrino oscillation experiment started in 2009. The neutrino beam produced at J-PARC (Japan Proton Accelerator Research Complex) is observed by both a near detector (ND280) and a far detector (Super Kamiokande), to produce an oscillation measurement. The main goal of T2K is to measure the unknown mixing angle θ_{13} by observing conversion from the muon-type neutrino to the electron-type neutrino. To achieve high sensitivity for this measurement, it is important to measure the initial neutrino beam properties at the near detector, located 280m from the neutrino production target. The near detector complex will measure the neutrino beam flux and energy spectrum prior to neutrino oscillation effects. The FGDs (Fine-Grained Detector) are main parts of the near detector complex. They consist of layers of scintillator bars and act as both a neutrino interaction target and as a tracking detector. The INGRID is another detector which will monitor the beam direction. It consists of scintillator layers and iron targets, and reconstructs the neutrino beam profile by counting the number of neutrino interactions in 16 identical modules. We started data-taking in the winter of 2009. The performance and commissioning of the FGD and the INGRID in the initial data taking is reported.

Key words: neutrino, neutrino oscillation, MPPC

1. The T2K experiment

The T2K experiment aims to measure unknown lepton mixing angle θ_{13} by measuring $\nu_\mu \rightarrow \nu_e$ oscillation probability. This oscillation mode is not yet observed, and only the upper limit for θ_{13} is measured: $\sin^2 2\theta_{13} < 0.15$ (90% C.L.) when $\Delta m^2_{13} \sim 2.4 \times 10^{-3}\text{eV}^2$[1]. The goal of T2K is to search down to $\sin^2 2\theta_{13} \sim 0.006$ (assuming $\Delta m^2_{12} = 7.6 \times 10^{-5}\text{eV}^2, \Delta m^2_{23} = 2.4 \times 10^{-3}\text{eV}^2, \delta_{CP} = 0$, normal hierarchy).
An overview of T2K experiment is shown in Fig. 1. The neutrino beam produced by J-PARC (Japan Proton Accelerator Research Complex) will be detected by both near and far detectors to measure neutrino oscillation. The combination of high intense neutrino beam produced by J-PARC proton accelerator and 50 kt gigantic water Cherenkov detector Super-Kamiokande provides high statistics measurement for neutrino oscillation. The near detector, located 280 m from neutrino production target, will measure the initial neutrino beam properties for precise measurement of neutrino oscillation .

2. The near detector complex

The near detector complex is designed to measure initial neutrino beam flux and energy spectrum. It consists of various types of detectors in order to detect several types of neutrino interaction (Fig. 2).
The main interaction mode at T2K beam energy is CCQE (Charge-Current Quasi Elastic) interaction $\nu + n \rightarrow l + p$. For

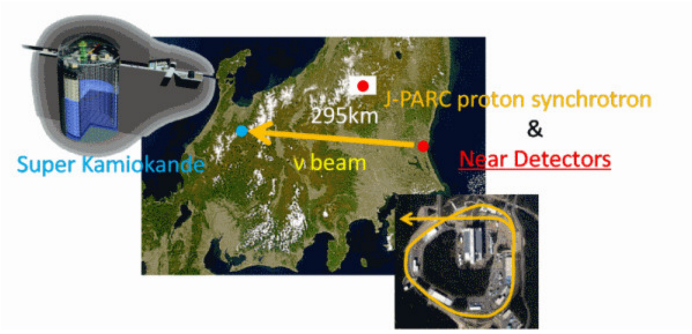

Figure 1: Overview of T2K experiment

these interactions, the energy of the initial neutrino can be easily reconstructed by measuring the direction and energy of final state lepton:

$$E_\nu = \frac{m_l^2 - 2E_l m_p}{2(E_l - m_p - p_l \cos\theta)}, \qquad (1)$$

where θ is the angle of lepton momentum with respect to the beam direction. However, there exist many other background processes. For example, the CC-1π ($\nu + n \rightarrow l + p + \pi$) process has an additional pion in the final state, and thus it is not easy to reconstruct the initial neutrino energy for this interaction. In Super-K, because in many cases only the lepton in the final state has its momentum above the Cherenkov threshold in water, it is hard to distinguish the CC-1π background events from CCQE events. Therefore the background event rates have to be measured in the near detector as well as CCQE interaction rate.

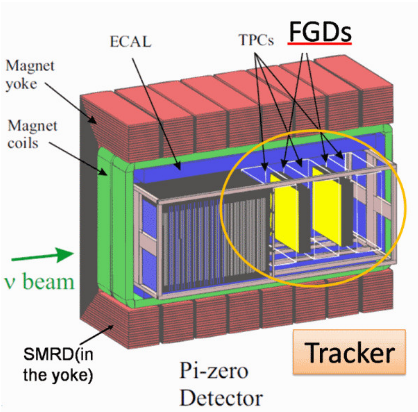

Figure 2: The near detector complex

In order to distinguish these interactions, it is important to detect the short tracks around the interaction vertex. The near detector contains three TPCs (Time Projection Chambers) and two FGDs (Fine-Grained Detectors) as a Tracker to detect these interactions (Fig. 3). The FGDs acts as the target of neutrino interaction as well as a tracking detector so that it can detect the particles around neutrino interaction vertex. The TPCs mainly detects the long track of leptons and measures its energy in 0.2 T magnetic field.

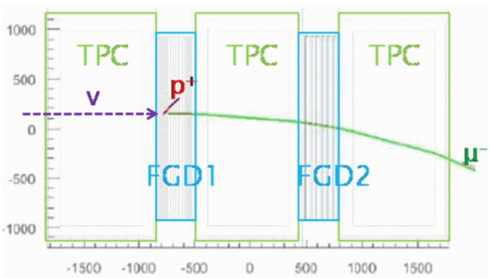

Figure 3: Simulated CCQE neutrino interaction in the Tracker

3. The Fine-Grained Detector

3.1. Overall design

The FGDs consist of finely segmented scintillator bars which are oriented in either the x and y direction, perpendicular to the beam direction (Fig. 4). Each plane consists of 192 bars and has dimensions of 184.3 cm × 184.3 cm × 0.96 cm. The X planes (vertical bars) and Y planes (horizontal bars) forms an "XY module". The first FGD contains 15 XY modules. The second FGD contains 7 XY modules alternating with 6 target water modules, in order to measure the neutrino interaction rate in water since the far detector Super-Kamiokande is a water Cherenkov detector.
The scintillator bars are 184.3 cm long and 0.96 cm × 0.96 cm in the cross-section. Each bar is made of polystyrene doped with PPO and POPOP, and were coated with TiO_2 for light reflection. Light from scintillator bars is collected and transmitted by Kuraray Y11 wavelength shifting (WLS) fibers. Then the photon detector MPPC (Multi-Pixel Photon Counter) detect the light from the WLS fibers at the end of the bars. The FGDs contain 8448 channels in total.
The XY modules and the target water modules hang inside the light-tight box called "dark box", which is made by aluminum. The read out electronics are mounted on the four sides of the FGDs, outside the dark box. In this way the heat producing elements are separated from the MPPCs, which have temperature dependence. The cooling water lines run through the four sides of the FGDs to keep the temperature stable.
The FGDs detects all the charged particles produced at the interaction vertex so that they can distinguish the type of neutrino interactions. Protons can be distinguished from muons and pions by dE/dx measurement. When the short proton track can be reconstructed, the CCQE selection purity can be improved by comparing the proton track angle to the expected angle for a CCQE interaction. Also short pion track can be identified by looking for the delayed hit of $\pi \to \mu \to e$ decay.

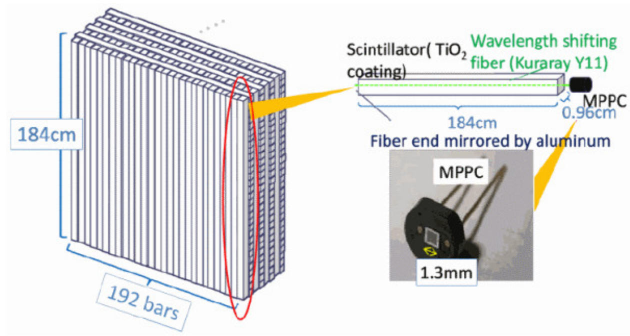

Figure 4: The Fine-Grained Detector

3.2. MPPC (Multi-Pixel Photon Counter)

Photon detectors for FGD have to read out 8448 channels inside the limited space in the magnet yoke, and they have to work in 0.2 T magnetic field. The MPPC, newly developed photon counting device manufactured by Hamamatsu photonics, fulfills these requirements. It consists of many small avalanche photo-diodes (APDs) in an area of typically 1 mm^2. Each APD pixel outputs a pulse signal when it detects one photon. The sum of the output of each APD pixel forms the MPPC output. We use the special type of MPPC, with a sensitive area of 1.3 × 1.3 mm^2 containing 667 pixels with 50 × 50 m^2 size each, which was developed for the T2K experiment. They were produced by Hamamatsu Photonics and their basic features were measured by the Kyoto group[2]. The major specifications of T2K-MPPC are summarized in Tab. 3.2.
The MPPC generates few photo-electron noise signals even if there are no input photons. We measure and monitor the gain of each channel by these noise signals. Bias voltages for the MPPCs are adjusted so that 1 p.e. pulse height is uniform for all the channels. Since the gain has temperature dependency, we measure the temperature by the sensors mounted on the bus-boards and correct the bias voltage. All the MPPC channels were tested and monitored in the detector, and more than 99.5% of them are working correctly.

Item	Spec.
Active area	1.3×1.3 mm^2
Pixel size	$50 \times 50\ \mu$ m^2
Number of pixels	667
Operation voltage	~ 70 V
Gain	$10^6 \sim 10^6$
Noise rate	$10^5 \sim 10^6$ Hz
PDE	30 ~ 50 %

Table 1: Specifications of T2K-MPPC

3.3. Read out electronics

Figure 5 shows the overview of FGD front end read out electronics system. All the MPPCs are mounted on the "bus-

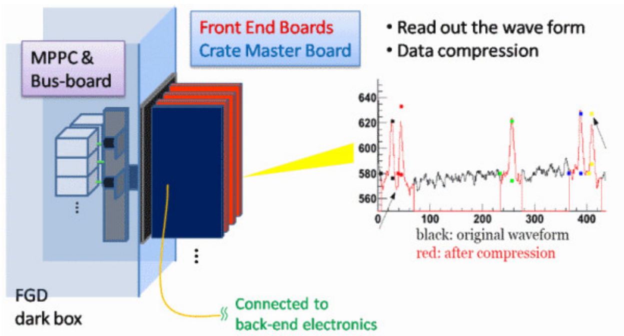

Figure 5: FGD readout electronics (front-end side)

boards" at the end of each scintillator bar. On the bus-boards, the MPPCs are connected to the fibers via optical connectors. The bus-boards also contain temperature sensors and LEDs for calibration of the MPPCs.
The Front End Board (FEB) controls and reads out the signal from the MPPCs. It contains special ASIC chip called AFTER (ASIC For TPC Electronics Readout) which performs 50 MHz waveform digitization for MPPC readout. The SCA (Switched Capacitor Array) in the AFTER ASIC chip can record the waveform continuously for 10 μs, to achieve an acceptance for delayed electron hit from $\pi \rightarrow \mu \rightarrow e$ decay.
The Crate Master Board (CMB) controls the FEBs, receive the data from FEBs and transfer to the back-end electronics outside the magnet. It can also compress the data by recording the waveform only around the pulses.

4. The INGRID beam monitor

Direction of neutrino beam will be monitored by INGRID (Interactive Neutrino GRID) detector. The INGRID consists of 16 identical modules. Fourteen of them are aligned in the shape of a cross, and two of them sits at the position separated from the cross (Fig. 6). Neutrino beam profile can be reconstructed from the number of neutrino interactions in each module. At designed beam intensity, the INGRID can provide a daily measurement of beam direction with precision better than 1 mrad.

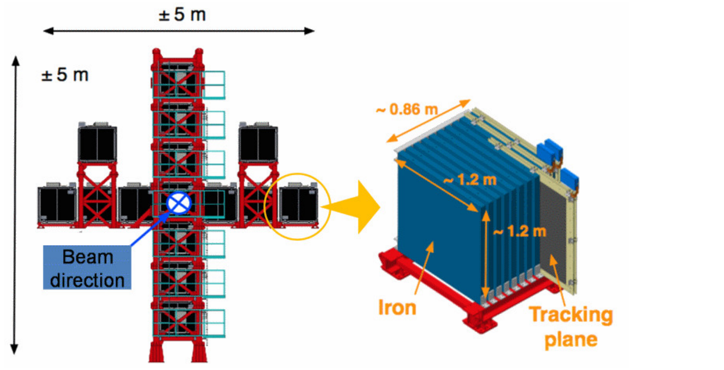

Figure 6: The INGRID detector

It samples the beam on ±5 m × ±5 m area to cover wide neutrino beam range.
Similar to the FGD, the INGRID modules are also composed of scintillator bars, fibers and MPPCs. The big difference is that it contains target iron plates to increase neutrino interaction rate. Each module is a sandwich structure of iron and scintillators surrounded by the veto scintillator counters. The size of scintillator bars are $120 \times 5 \times 1$ cm^3, which is wider than the FGD. The total weight of the INGRID detector is ~110 tons, and total number of channels is 9592.
For the readout, we use a TRIP-t ASIC chip which integrates and store the MPPC signal. The TRIP-t chips are mounted on the front end boards, and one board handles 48 MPPC channels. Bias voltages for the MPPCs are also controlled by this board.

5. Beam commissioning

T2K started beam commissioning from April 2009. Fourteen INGRID modules were installed in August 2009, and the FGDs were installed in October 2009. Remaining 2 INGRID modules will be constructed and installed in summer 2010. The T2K first neutrino event was observed in November 2009 at the INGRID detector (Fig. 7). Also the FGDs successfully observed the neutrino event in December 2009 (Fig. 8).
T2K neutrino beam has a bunch structure. Each bunch is ~60

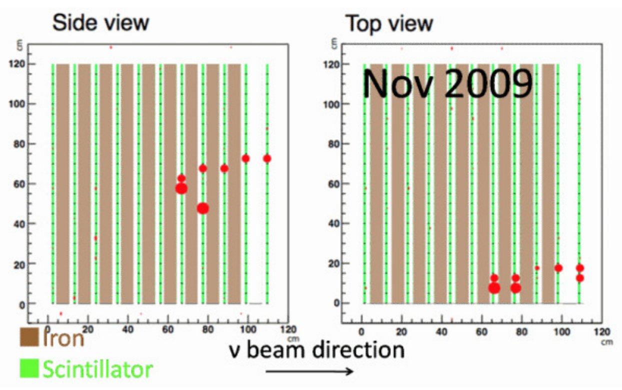

Figure 7: T2K first neutrino event candidate in the INGRID detector

ns wide and the bunch interval is ~600 ns. Figure 9 shows the

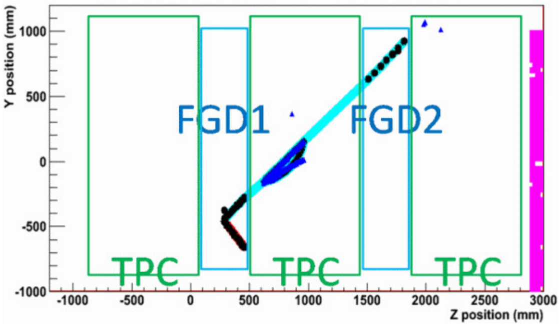

Figure 8: Observed neutrino event candidate in the Tracker

observed beam event timing distribution in FGD. The events which survived energy threshold cut and timing coincidence cut are filled in this histogram. We successfully observed neutrino candidate events around the expected beam timing, and confirmed that the detector is working correctly to detect neutrino events. Most of the observed beam events contained horizontal track which can be explained as the tracks of muons produced in the neutrino interaction outside the detector.
The INGRID also detected a lot of neutrino-related events.

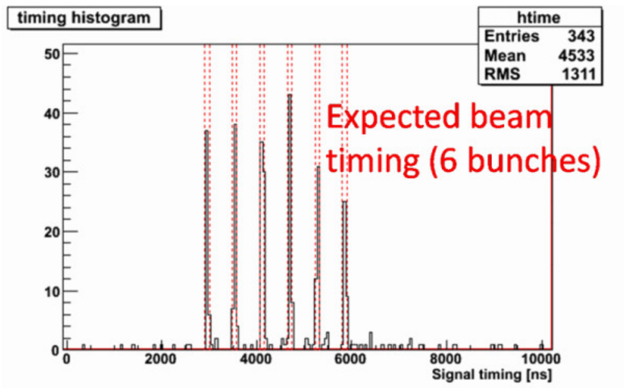

Figure 9: Beam event timing distribution at the FGD

Figure 10 shows the distribution of number of neutrino-related events detected in each INGRID module. At this stage we didn't have enough neutrino beam data to reconstruct the neutrino beam profile, but we confirmed that the neutrino events are correctly observed in the INGRID detector. Now that we confirmed that all the detectors are working correctly, we are ready for the physics run.

6. Summary

The T2K experiment is a long baseline neutrino oscillation experiment started in 2009. The near detector, located 280 m downstream from neutrino production target, will measure the initial beam properties for precise neutrino oscillation measurement.
The FGD is a main part of the near detector complex. It is composed of finely segmented scintillator bars, and capable of distinguishing the type of neutrino interactions by detecting all

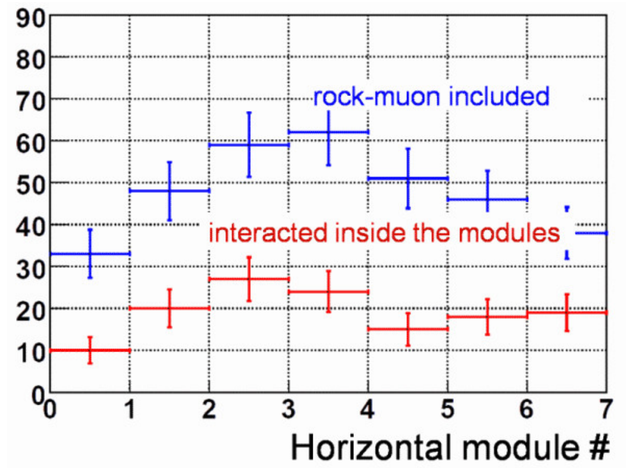

Figure 10: Distribution of neutrino-related events at INGRID

the charged particles around interaction vertex. The MPPC is compact photon counting device used in the near detectors. It can be used in the limited space of magnet yoke and works in magnetic field. To operate and read out the MPPC, we developed a Front-End Board which contains a special ASIC chip called AFTER ASIC chip. It controls the bias voltage for individual MPPCs, and read out the wave form continuously for 10 μs, in 50 MHz.
There is another near detector called INGRID, which will monitor the beam direction with precision better than 1 mrad. It consists of 16 identical modules, and each of the modules is a sandwich structure of iron and scintillator tracking plane. The beam profile is reconstructed by counting the number of neutrino interactions for each module. The FGD and 14 INGRID modules are installed in 2009 autumn, and successfully observed neutrino-candidate events during the commissioning run. The detectors are now ready for the physics run.

References

[1] M. Apollonio et al. (CHOOZ Collaboration). Search for neutrino oscillations on a long base-line at the chooz nuclear power station. Eur. Phys. J., Vol. C27, p. 331, 2003.
[2] M. Yokoyama el al. Nucl. Instrum. Meth A610, 362 (2009) "Mass production test of Hamamatsu MPPC for T2K neutrino oscillation experiment"