T2K experiment: Status and first results

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Abstract. The long baseline neutrino oscillation experiment T2K, which uses a high intensity off-axis muon neutrino beam produced at JPARC, aims at a discovery of oscillation of muon neutrinos into electron neutrinos and measurement of the mixing angle $\theta_{13}$, a key parameter for further search for CP violation in the lepton sector. T2K is also designed to precisely measure the oscillation parameters $\Delta m_{23}^2$ and $\theta_{23}$ in a disappearance oscillation mode. The major components of T2K include a neutrino beam line, muon monitors, a near detector complex ND280 located at 280 m from the proton interaction target, and the far detector Super-Kamiokande (295 km from the neutrino source), at a 2.5 degree off-axis angle from the beam. The measured neutrino spectrum at ND280 and measurements of the primary proton beam combined with the NA61 hadron production data will be used to predict the unoscillated spectrum at Super-Kamiokande. The oscillation analysis will be done by comparing the observed and predicted spectra at the far detector. The construction of the T2K neutrino beam line and the near neutrino detectors is completed. For the first data taking period with the neutrino beam, about $3 \times 10^{19}$ 30 GeV protons on target were accumulated. The design, performance, current status of the experiment and near future perspectives will be discussed. The results of the first physics run will be presented.

1. Introduction
The Tokai to Kamioka (T2K) experiment is a long baseline muon neutrino beam experiment located in Japan. The main components of T2K include a neutrino beam line, muon monitors, a near detector complex ND280 located at 280 m from the proton interaction target, and the far detector Super-Kamiokande (295 km from the neutrino source), at a 2.5 degree off-axis angle from the beam. The main goals of the experiment are to measure the mixing angle $\theta_{13}$ for the first time, and to improve the measurement of $\theta_{23}$ and $\Delta m_{23}^2$. In addition, several neutrino cross-section studies will be conducted with the near detector. In these proceedings, I will describe the current status of the experiment and the data collected in the first run which started in January 2010 and ended in June 2010.

2. Overview of the T2K experiment
A schematic view of the experiment is present in Fig. 1. Protons are accelerated to 30 GeV throughout the Tokai accelerator complex, and collide on a graphite target. From these collisions pions are created. Positive pions are selected and focused with a series of three magnetic horns. These pions then decay into muon and muon neutrinos inside a 94 m long decay tunnel. The muons are observed with the muons monitors, 120 m away from the target. The neutrino near detector is located 280 m away from the target (which explains its name: ND280). It consists of two parts: the on-axis and the off-axis detector. As their names suggest, the on-axis near
detector (INGRID) is on axis with the neutrino beam, while the off-axis near detector is at a 2.5° off-axis angle from the neutrino beam. A more detailed description of the near detector is given in Section 5 and in the ND280 technical design report [1]. Finally, the far detector (Super-Kamiokande) is located 295 km away and at a 2.5° off-axis angle from the target.

3. Physics goals
The physics goals of T2K are to improve the measurement of $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$ using the $\nu_\mu$ disappearance analysis, and to measure for the first time the $\theta_{13}$ oscillation parameter through the $\nu_e$ appearance analysis. The sensitivity of the T2K experiment for the measurement of $\theta_{13}$ is presented in Fig. 2 and Fig. 3. In addition the near detector will be able to improve neutrino cross-section measurements around 750 MeV.

Figure 1. Overview of the T2K experiment.

Figure 2. T2K sensitivity to $\theta_{13}$ at the 90% confidence level as a function of protons on target. 5%, 10% and 20% systematic error fractions are plotted. The dashed arrow indicates a 5-year run at 750 kW. The following oscillation parameters are assumed: $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$, $\delta m_{12}^2 = 7.6 \times 10^{-5} eV^2$, $\delta m_{23}^2 = 2.4 \times 10^{-3} eV^2$, $\delta_{CP} = 0$, normal hierarchy.

Figure 3. T2K sensitivity to $\theta_{13}$ at the 90% confidence level as a function of $\Delta m_{23}^2$. Beam is assumed to be running at 750kW for 5 years, using the 22.5 kton fiducial volume SK detector. 5%, 10% and 20% systematic error fractions are plotted. The yellow region has already been excluded to 90% confidence level by the Chooz reactor experiment. The oscillation parameters are the same as in Fig. 2.
3.1. Oscillation analysis strategy
Both oscillation analyses rely on the comparison of the data collected at the near detector and the data collected at the far detector. The number of events at the far detector can be estimated using the following equation:

\[ N(E_{\text{rec}}^{\nu}) = \Phi_{\text{exp}}^{SK}(E_{\text{true}}^{\nu}) \times \sigma(E_{\text{true}}^{\nu}) \times P_{\text{osc}}(E_{\text{true}}^{\nu}) \times \epsilon_{SK}(E_{\text{true}}^{\nu}) \times f(E_{\text{rec}}^{\nu}, E_{\text{true}}^{\nu}), \]

where \( \Phi_{\text{exp}}^{SK} \) is the expected flux at SK, \( \sigma(E_{\text{true}}^{\nu}) \) the neutrino cross-section, \( P_{\text{osc}}(E_{\text{true}}^{\nu}) \) the oscillation probability, \( \epsilon_{SK}(E_{\text{true}}^{\nu}) \) the efficiency to detect a neutrino at SK and \( f(E_{\text{rec}}^{\nu}, E_{\text{true}}^{\nu}) \) is the energy response function. The expected flux at SK, \( \Phi_{\text{exp}}^{SK} \), is given by \( \Phi_{\text{exp}}^{SK} = R_{SK/ND} \times \Phi_{ND} \)
and the near detector flux, \( \Phi_{ND} \), is given by \( \Phi_{ND} = \frac{N_{\text{obs}}^{ND}}{\sigma_{ND} \times \epsilon_{ND}} \). In order to know \( \Phi_{ND} \) reliably, we need inputs from the hadron production experiment NA61, and we need to know neutrino cross-sections (\( \sigma_{ND} \)). We will use neutrino cross-sections measured by other experiments, like SciBooNE, but also by the T2K near detector. The flux at SK, \( \Phi_{SK}^{exp} \), relies on a good understanding of the normalization and of the neutrino energy spectrum of the near detector data, and a good understanding of the far/near ratio (\( R_{SK/ND} \)).

4. Beam commissioning for the 2010a run
The T2K experiment started to take data in January 2010. The first run lasted from January to June 2010 and accumulated \( 3.23 \times 10^{19} \) protons on target (POT) at 30 GeV. The beam was run stably at 50 kW and we also achieved powers of 100 kW. During this running period, the Super-Kamiokande detector and the INGRID detector were 99% efficient and the off-axis near detector was very stable after it started running in February 2010. An overview of the 2010a run is presented in Fig. 4.

![Figure 4](image_url)

Figure 4. Number of protons on target during the 2010a data-taking period. Yellow points are the number of proton per pulse and should be read with the scale on the right side of the plot.

5. Current status of the near detector (ND280)
An overview of the near detector is presented in Fig. 5 and a detailed view of the off-axis near detector is presented in Fig. 6. The purpose of the on-axis INGRID detector is to monitor the
direction of the beam by looking at neutrinos themselves. The off-axis near detector is located inside 0.2 Tesla magnetic field produced by the UA1/NOMAD magnet. It consists of several fine grained detectors and trackers. All sub-detectors were installed in 2009 and ready for data-taking in 2010 apart from the barrel ECAL which was installed in summer 2010. The purpose of the off-axis near detector is to:

- measure charge-current interactions from beam muon neutrinos in order to do the normalization with the far detector.
- measure charge-current interactions from beam electron neutrinos in order to predict the background contamination for the $\nu_e$ appearance analysis.
- measure neutrino cross-sections.

**Figure 5.** General view of the near detector.

**Figure 6.** General view of the off-axis near detector.

### 5.1. INGRID
As stated before, the main purpose of the INGRID detector is to monitor the beam with neutrinos themselves and at off-axis angles ranging from 0 to 2.5 degrees. Data collected with the INGRID detector tell us that the neutrino beam for the 2010a run was where we expected it to be. Figure 7 and Fig. 8 show the horizontal and vertical beam profile and that the neutrino beam is properly centered.

### 5.2. Time projection chambers (TPC) and Fine-grained detector (FGD)
The time projection chambers (TPC) and the fine grained detector (FGD) form the tracker part of the off-axis near detector. The 2 FGDs act as an active target and give timing information while the TPCs allow for particle identification, charge, and momentum determination. There are 3 TPC modules and they have a sensitive area of $1.8 \times 2 \times 0.70$ m$^3$. The readout is handled through MicroMeGas modules with about 124,000 channels. The TPCs particle identification
performance is presented in Fig. 9 for negative particles and Fig. 10 for positive particles. The TPCs have been described in great detail in a NIM paper submitted in December 2010 [2]. There are 2 modules of fine-grained detector with $2 \times 1.3$ tons of active target. The first FGD is only made of plastic, while the second has plastic and water. The scintillation light is detected by Geiger-mode avalanche photo-diode multi-pixel photon counter (MPPC). There are about 9500 channels.

5.3. The $\pi^0$ detector (P0D), electromagnetic calorimeter (ECAL and DSECAL), Side muon range detector (SMRD) performance

The $\pi^0$ detector, the downstream electromagnetic calorimeter (DSECAL) and the side muon range detectors have all been installed prior to the 2010a data taking run and were operating smoothly during the run. The remaining part of the electromagnetic calorimeter, the barrel ECAL, was installed over the summer of 2010 and is functioning well since we restarted taking data in November 2010.

5.4. Selection of event displays from the 2010a run

In Fig. 11, we present a selection of events collected with the off-axis near detector during the 2010a run. It can be seen that all sub-detectors of the off-axis near detector are functioning
properly.

Figure 11. ND280 event displays with possible interactions types. Top left: deep inelastic scattering event in FGD1 + cosmic muon. Top right: CCQE event in FGD1. Bottom left: CC single π event in FGD2. Bottom right: deep inelastic scattering event in FGD1.

6. Current status of the far detector (Super-Kamiokande)
The Super-Kamiokande detector is located close to the town of Kamioka in the Gifu prefecture in Japan. It is a well-known water Cherenkov neutrino detector which consists of a 50 kton water tank with a 22.5 kton fiducial volume. There are about 11,000 PMT's facing inward and looking for neutrino interactions that happen in the inner detector. There are also about 2000 PMT’s facing outward to look for light coming from interactions which happen in the outer detector (a 2.5 m wide shell around the inner detector). The outer detector data is used as a veto for cosmic ray muons. The Super-Kamiokande detector has been described in great detail in a NIM paper in 2003 [3].

6.1. Performance of the Super-Kamiokande detector
After about 15 years of running, the Super-Kamiokande detector is now very well understood. During the 2010a data taking period, it was running very reliably. Among others, the water transparency, the electronics, the energy scale calibration and the water scattering parameters were closely monitored and considered perfectly adequate for normal data taking. The event rate and timing distributions of the events collected by the Super-Kamiokande detector during the 2010a run are presented in Fig. 12 and Fig. 13. Fig. 12 shows the data collected within 1 millisecond of the T2K beam spill. We can see that the low energy data (LE) is flat, and so are the outer detector data (OD). For the T2K analyses, we will use only events that are fully-contained in the inner detector (FC) and we can see that such events happen only during the 3 µs T2K beam spill and we therefore have no atmospheric neutrino contamination. Fig. 13 shows the bunch structure of the spill and the distribution of the FC events among the bunches.

6.2. Summary of analysis cuts for the far detector dataset
To perform the $\nu_\mu$ disappearance analysis and the $\nu_e$ appearance analysis, a set of cuts was fixed before data taking began and are summarized in Table 1. The first four cuts are common to
Table 1. Summary of cuts applied for both appearance and disappearance analyses.

|                      | For $\nu_\mu$ disappearance | For $\nu_e$ appearance |
|----------------------|------------------------------|------------------------|
| Timing coincident with beam time + (TOF) | Timing coincident with beam time + (TOF) | Timing coincident with beam time + (TOF) |
| Fully contained (no OD activity) | Fully contained (no OD activity) | Fully contained (no OD activity) |
| Vertex in fiducial volume (2 m from the wall) | Vertex in fiducial volume (2 m from the wall) | Vertex in fiducial volume (2 m from the wall) |
| Single ring event | Single ring event | Single ring event |
| Visible energy ($E_{vis}$) > 30 MeV | Visible energy ($E_{vis}$) > 100 MeV | Visible energy ($E_{vis}$) > 100 MeV |
| $\mu$-like ring | $e$-like ring | $e$-like ring |
| No decay electron | No decay electron | No decay electron |
| Invariant mass of forced 2nd ring < 105 MeV | Invariant mass of forced 2nd ring < 105 MeV | Invariant mass of forced 2nd ring < 105 MeV |
| $E_\nu < 1250$ MeV | $E_\nu < 1250$ MeV | $E_\nu < 1250$ MeV |

both analyses. We select events that are within the timing window of the T2K beam spill, that are fully contained inside the Super-Kamiokande inner detector (ie. we allow less than 16 hits in the outer detector). We also require that the vertex is reconstructed more than 2 m away from the inner wall of the detector to ensure proper reconstruction of the events. Finally we require single ring events. For the $\nu_\mu$ disappearance analysis, we then require a visible energy greater than 30 MeV and that the ring found is $\mu$-like. For the $\nu_e$ appearance measurement, we require a visible energy greater than 100 MeV, and that the ring found is $e$-like. In addition we ask for no decay electron, and if we force our algorithm to look for a second ring, we ask that the invariant mass of the found ring and the forced ring be below 105 MeV to reject neutral pions.
decaying to two photons. Finally we ask that the reconstructed neutrino energy be smaller than 1250 MeV to limit background contamination from higher energy.

6.3. Overview of the 2010a dataset collected by the Super-Kamiokande detector
During the 2010a run, 33 events in time with the T2K beam and fully-contained (FC) inside the inner detector were found. Out of these 33 events, 23 events pass the fiducial volume cut and the requirement that the visible energy be greater than 30 MeV. Fig. 14 and Fig. 15 show the distributions of these 33 events inside the Super-Kamiokande detector.

![Figure 14](image1.png)  
**Figure 14.** Vertex distributions (XY projection) of FC events. The dots are the reconstructed vertices, the blue arrows are the reconstructed direction from the ring. The red arrow is the direction of the T2K beam.

![Figure 15](image2.png)  
**Figure 15.** Vertex distributions (RZ projection) of FC events. The dots are the reconstructed vertices, the arrows are the reconstructed direction from the ring.

7. Conclusions
The first data-taking run of the T2K experiment has been very successful. We accumulated $3.23 \times 10^{19}$ proton on target at 30 GeV, and the proton intensity is increasing steadily. The performances of both the near detector and the far detector have been superb during the entire data-taking period. After the 2010a run, the barrel ECAL installation was completed and we started a new data-taking run in November 2010, at around 100 kW. The T2K experiment aims to accumulate an integrated proton power on target of $150 \text{kW} \times 10^7$ seconds by July 2011.

8. References
[1] URL http://www.nd280.org/info
[2] T2K ND280 TPC collaboration (Preprint arXiv:1012.0865 (2010))
[3] Fukuda Y et al. 2003 Nucl. Instrum. Meth. A501 418–462