

Chapter 2

Overview of the T2K Experiment

The T2K experiment is an accelerator based long baseline neutrino oscillation experiment started physics data taking in 2010. The intense ν_μ beam is produced by J-PARC (Japan Accelerator Research Complex) proton accelerator at Tokai. We detect the neutrinos at both the near detector “ND280” and the far detector “Super-Kamiokande” (SK) (Fig. 2.1). Neutrino oscillation probability is determined by measuring the neutrino beam before and after oscillation at the near and far detectors, respectively.

The main goals of the T2K experiment are as follows:

Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation

Before the discovery of non-zero θ_{13} in 2012, our primary goal was to extend the θ_{13} search down to $\sin^2 2\theta_{13} \sim 0.008$ by the measurement of $\nu_\mu \rightarrow \nu_e$. Nowadays, θ_{13} is already measured to be $\sin^2 2\theta_{13} = 0.098 \pm 0.013$ [2]. Then, in order to determine the value of δ_{CP} , the precise measurement of $\nu_\mu \rightarrow \nu_e$ become more important. Currently, our motivation of this measurement is to discover $\nu_\mu \rightarrow \nu_e$ with more than 5σ significance, and to measure δ_{CP} .

Precise measurement of oscillation parameters in $\nu_\mu \rightarrow \nu_\mu$ oscillation

Our goal of the $\nu_\mu \rightarrow \nu_\mu$ measurement is to determine the values of θ_{23} and Δm_{32}^2 with an accuracy of 1 and 3 %, respectively. This is important not only to explore the physics behind the mixing pattern, but also for the measurement of δ_{CP} because the CPV term in $P(\nu_\mu \rightarrow \nu_e)$ is proportional to $\sin \theta_{13} \sin \theta_{23} \sin \theta_{12} \sin \delta_{CP}$. In our current best knowledge, the uncertainty of θ_{23} is the largest among three mixing angles.

The main feature of the T2K experiment is that we use high intensity neutrino beam and gigantic water Cherenkov detector (SK) which provides high statistics of neutrino events. The other important feature is that we use “off-axis beam” which enables to obtain a neutrino beam with sharp energy spectrum peaked at the energy which maximizes the neutrino oscillation probability. In this chapter, we describe those important features while explaining the overview of the T2K beamline and detector configurations.

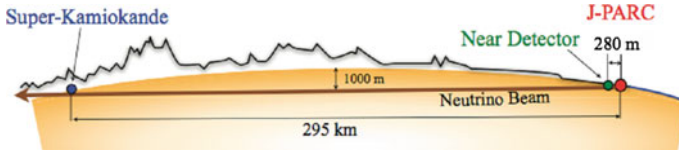


Fig. 2.1 The overview of the T2K experiment [1]

2.1 J-PARC Neutrino Beam Line

The layout of the J-PARC accelerators is shown in Fig. 2.2. The protons are accelerated through linear accelerator (LINAC), 3 GeV proton-synchrotron (RCS), and main ring (MR). The proton beam is extracted from the MR to the neutrino beam line. In the neutrino beamline, the beam is shaped by 11 normal conducting magnets, bent to the direction of SK by 14 superconducting magnets, and transported to the neutrino production target by 10 normal conducting magnets. The protons generate the pions by the interaction on target, and the pions decay to μ and ν_μ to produce a ν_μ beam.

Figure 2.3 shows the overview of the neutrino beam line and the near detectors. The protons smash the graphite target and produce secondary pions. The directions of pions are focused by three electro-magnetic horns [3]. The target sits inside the first horn, and the second and third horns are placed at the downstream of the target.

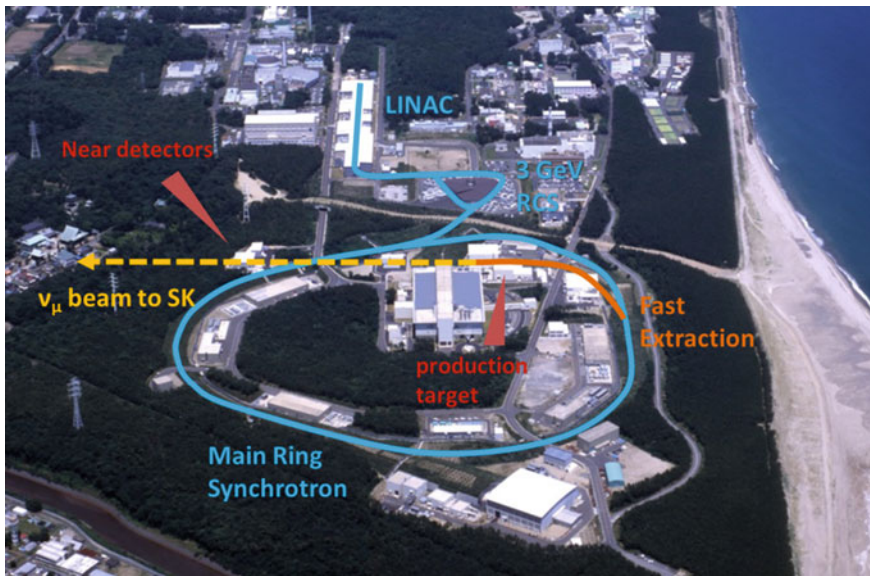


Fig. 2.2 Bird's eye view of J-PARC

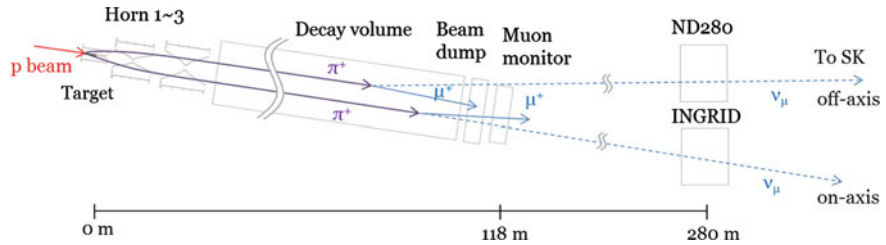


Fig. 2.3 Neutrino beam line and the near detectors

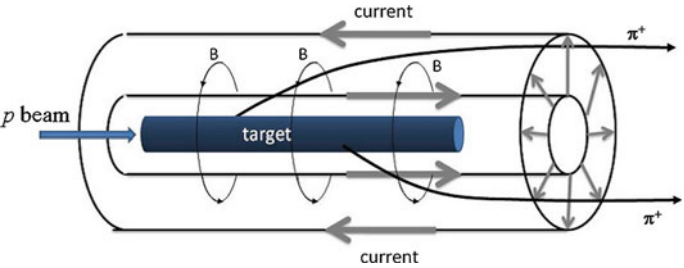


Fig. 2.4 Illustration of the first horn. The graphite target sits inside the first horn. The positively charged particles produced by the proton beam are focused in the forward direction due to the magnetic field

The positive pions are focused to the forward direction (Fig. 2.4), while the negative pions are de-focused. Then the pions decay to neutrinos in the 94 m long decay region ($\pi \rightarrow \mu + \nu_\mu$). At the end of the decay volume, the remaining protons and pions are absorbed by the beam dump. Only the neutrinos and high energy muons will penetrate the beam dump. The muon monitor sits at the 118 m downstream of the beam target and measures the muon beam flux and direction. The near detectors called “ND280” and “INGRID” measure the neutrino beam at 280 m downstream of the target. As we explain in Sect. 2.1.2, the direction of SK is shifted by 2.5° from the direction of the proton beam, because we use the “off-axis” method.

Table 2.1 Summary table of beam parameters

Parameter	Design value	Present value in May 2013
Beam energy	50 GeV	30 GeV
Beam power	0.75 MW	0.22 MW
Spill interval	~ 3.3 s	2.48 s
Number of protons	$3.3 \times 10^{14}/\text{spill}$	$1.2 \times 10^{14}/\text{spill}$
Number of bunches	8 bunches/spill	8 bunches/spill
Bunch interval	581 ns	581 ns
Bunch width	58 ns	58 ns

The T2K beam parameters are listed in Table 2.1. The current beam power is 220kW, while the designed value is 750kW. The beam power will increase in the future by increasing the number of protons per bunch and the repetition rate, by upgrading the LINAC, the MR magnet power supply and the MR RF core.

2.1.1 Controlling the Primary Proton Beam

The proton beam is controlled by using many beam monitors which are placed in the beamline. Figure 2.5 shows the locations of the beam monitors. The beam intensity, position, profile and loss are monitored by the current transformers (CT), electro-static monitors (ESM), segmented secondary emission monitors (SSEM) and beam loss monitors (BLM), respectively. The optical transition radiation (OTR) monitor which is placed just upstream of the target measures the beam profile. Figure 2.6 shows the illustrations of CT, ESM, SSEM and OTR. We describe each of the monitor below.

Current transformer (CT)

The CT is a 50-turn toroidal coil around a cylindrical ferromagnetic core. It measures the current induced by the toroidal magnetic field induced by the proton beam. The beam intensity is measured by CT with 2 % accuracy.

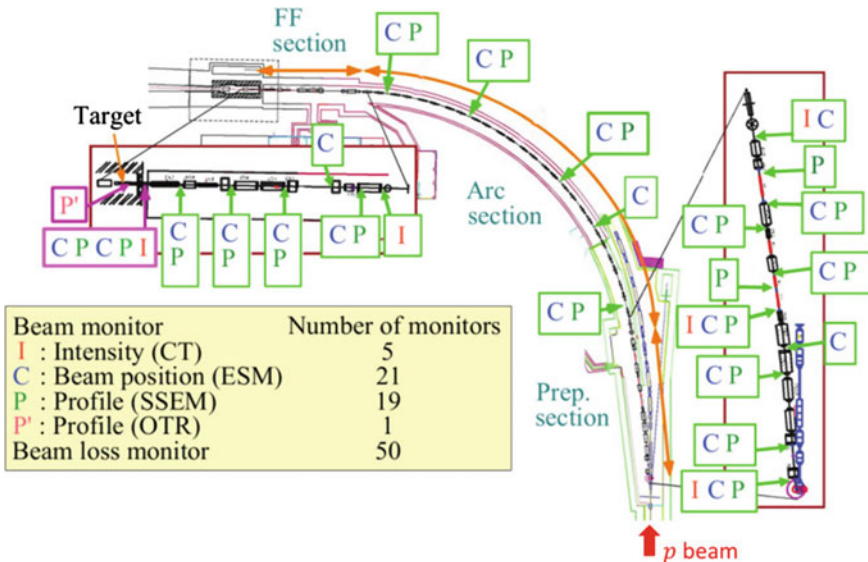


Fig. 2.5 Locations of the beam monitors [1]

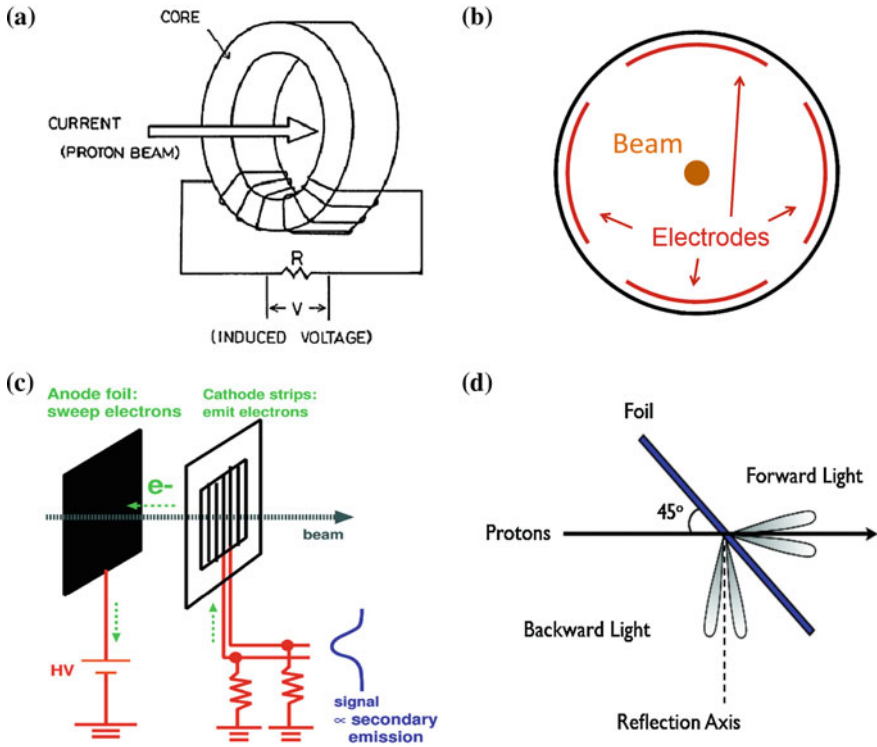


Fig. 2.6 Illustrations of **a** the CT, **b** the ESM, **c** the SSEM and **d** the OTR

Electro-static monitor (ESM)

The ESM has four segmented cylindrical electrodes surrounding the proton beam. By measuring the induced current, it measures the beam position with better than $450\mu\text{m}$ accuracy.

Segmented secondary emission monitor (SSEM)

The SSEM is made of $5\mu\text{m}$ titanium foil strips oriented in horizontal and vertical directions. The interaction of protons with the foil produces secondary electrons which induce currents on strips that can then be measured. Since they cause a beam loss, they are inserted only during the beam tuning and removed in the physics data taking except for the one which is placed at most downstream of the beam line.

Beam loss monitors (BLM)

The BLM is a gas filled proportional counters. The beam abort signal is fired when the beam loss become too large.

Optical transition radiation monitor (OTR)

The OTR [4] measures the beam profile with $50\mu\text{m}$ thick titanium alloy foil placed at 45° to the incident proton beam. The beam crossing the foil produces transition radiation. Profile of the proton beam is measured by imaging the light using a system of parabolic mirrors and camera.

2.1.2 Off-Axis Method

One of the important features of T2K is the off-axis beam. As shown in Fig. 2.3, the direction of neutrino beam is shifted by $\sim 2.5^\circ$ from the direction of SK. The direction of proton beam is called “on-axis”, while the direction of SK is called “off-axis”.

When a neutrino is produced from the decay of a pion $\pi \rightarrow \mu + \nu_\mu$ in the direction of off-axis angle θ_{OA} with respect to the initial pion direction, the energy of the neutrino can be derived from following equation:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - P_\pi \cos \theta_{OA})}. \quad (2.1)$$

With a finite off-axis angle, the neutrino energy becomes almost independent of parent pion momentum (Fig. 2.7). Figure 2.8 shows the simulated neutrino energy spectrum with different off-axis angles and the oscillation probability as the function of neutrino energy. By using the off-axis method and adjusting the off-axis angle, we can maximize the signal to background ratio by making the narrow neutrino energy

Fig. 2.7 Neutrino energy in the function of the momentum of parent pion, for different off-axis angles

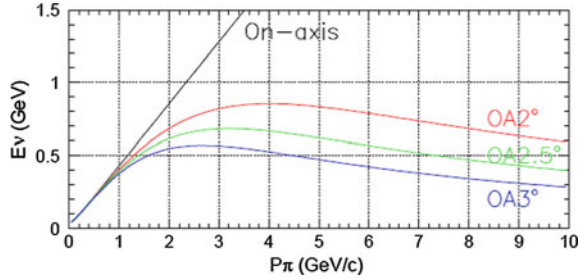
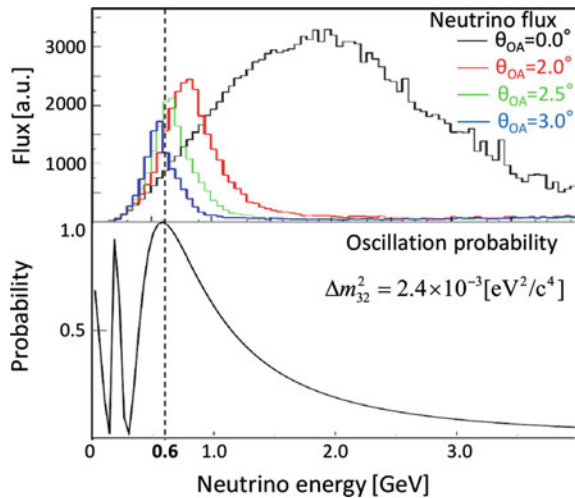


Fig. 2.8 The neutrino energy spectrum for different off-axis angles (*top*) and the oscillation probability in the function of neutrino energy (*bottom*)



spectrum with a peak at the oscillation maximum, while reducing the backgrounds from high energy neutrino interactions. However, this method requires to carefully monitor the beam angle because the beam energy strongly depends on the beam direction.

2.2 Monitoring of the Secondary Beam

The direction and intensity of the neutrino beam are monitored by the muon monitor [5] and the INGRID detector [6], to ensure high quality neutrino beam.

2.2.1 Muon Monitor

The muons which penetrates the beam dump are measured by the muon monitor (MUMON), which is placed just behind the beam dump. While the INGRID monitors the neutrino beam by directly measuring it, MUMON indirectly monitor the neutrino beam by detecting muons which are produced together with neutrinos. The advantage of measuring the muon beam is that it makes it possible to monitor the neutrino beam direction in spill-by-spill basis, while the INGRID can only measure the beam direction in day-by-day basis at the designed beam power.

The MUMON monitors the intensity, profile and direction of the muon beam with the combination of ionization chambers array and silicon PIN photo-diodes array (Fig. 2.9). In each array, there are 7×7 sensors at 25 cm intervals. The ionization chambers are suitable to the muon beam measurement because they are made out of radiation tolerant material. However, it requires fine control of the gas quality to have a stable response. On the other hand, the silicon diodes are easy to handle, but the stability of the response is affected by the radiation. Therefore, the combination of two types of detectors provides complementary measurements. The precisions of muon flux intensity and direction measurement is estimated to be $\sim 0.1\%$ and 0.25 mrad, respectively.

2.2.2 INGRID

The initial beam properties are measured by the near detectors, located at 280m downstream from the neutrino production target, ~ 30 m underground in the pit. The near detector consists of the on-axis detector INGRID and the off-axis detector ND280 (Fig. 2.10). The INGRID detects neutrino interactions to measure the neutrino beam direction and the stability of the beam.

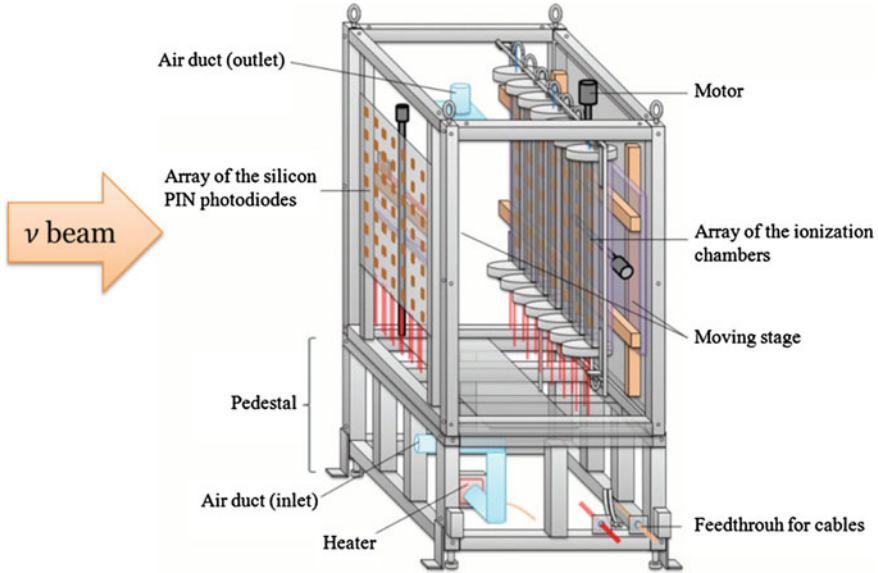
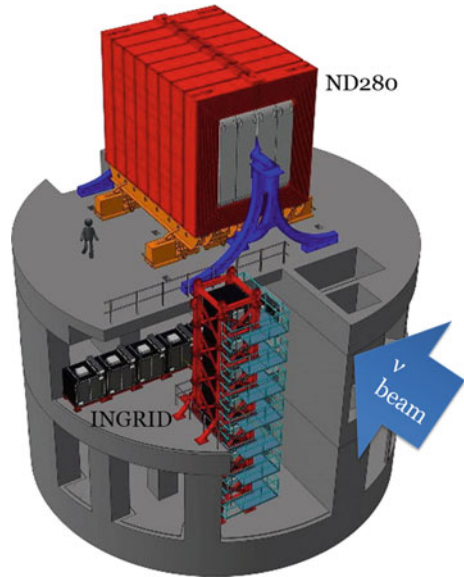


Fig. 2.9 Schematic view of MUMON. Neutrino beam comes from the *left* side of the figure

Fig. 2.10 The near detectors located at 280 m downstream from the neutrino production target



The RMS width of the neutrino beam at the near detector pit is ~ 5 m. In order to monitor the neutrino beam, INGRID is designed to cover a wide region with large mass. Figure 2.11 shows the schematic view of the INGRID. It consists of 16 identical modules: seven horizontal modules, seven vertical modules and two off-

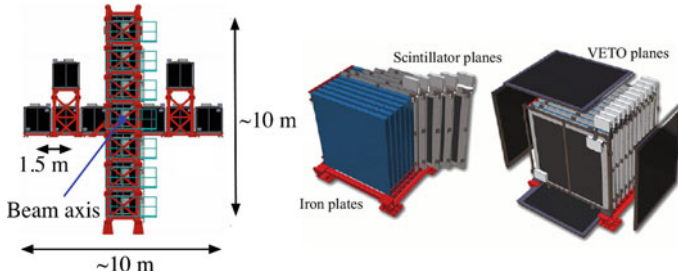


Fig. 2.11 The INGRID detector

cross modules. The total width $\times$ total height is $\sim 10\text{ m} \times 10\text{ m}$. The beam direction is obtained by measuring the profile center of the neutrino beam. Each module is made of alternating plastic scintillators tracking planes and iron plates. The total iron mass serving as a neutrino target is 7.1 tons per module and ~ 114 tons for all the modules.

The light signals from the scintillators are read out by a photon sensor called MPPC (Multi-Pixel Photon Counter). There are in total 9592 channel of MPPCs used in the INGRID, and they are also used in the ND280 detector. The detail of the MPPC is described in Chap. 3.

2.3 ND280 and Super-Kamiokande

The ND280 detector measures the neutrino interactions before oscillations, while the SK measures the neutrino interactions after oscillations.

2.3.1 Neutrino Detection at ND280 and SK

Before explaining the detail of the ND280 and SK, we describe the neutrino interaction modes which are relevant to the measurements in T2K. When we measure the neutrino beam at ND280 and SK, the flavour of neutrino is identified from the type of leptons (l) in the final state of neutrino–nucleus charged current (CC) interaction. For example, the following interaction is called CCQE (Charged Current Quasi-Elastic) interaction.

$$\nu_l + n \rightarrow l^- + p \quad (2.2)$$

There are also other interaction modes. For example:

$$\nu_l + n \rightarrow l^- + n + \pi^+ \quad (2.3)$$

$$\nu_l + n \rightarrow \nu_l + n + \pi^0 \quad (2.4)$$

The first one is called CC1 π (Charged Current 1 pion) interaction, and the second one is called NC1 π^0 (Neutral current 1 π^0) interaction. As we describe in Chap. 3 and Sect. 7.1, we select CCQE interaction as a signal, and the CC1 π and NC1 π^0 interactions are the main background interaction modes. The uncertainty of the cross sections for each interaction mode must be constrained by measuring these interactions at the ND280 detector.

2.3.2 ND280

The ND280 (Near Detector at 280 m) is designed to measure the initial neutrino beam flux, energy spectrum and the neutrino–nucleus cross sections for several different interaction modes. It consists of various types of detectors suited inside the magnet (Fig. 2.12).

- Magnet

ND280 uses the magnet which was donated from the UA1 experiment at CERN. It supplies a magnetic field of 0.2 T to measure the momenta and charges of the charged particles produced in neutrino interactions. The inner size of the magnet is 3.5 m $\times$ 3.6 m $\times$ 7.0 m. The magnetic coils are made of aluminum bars with

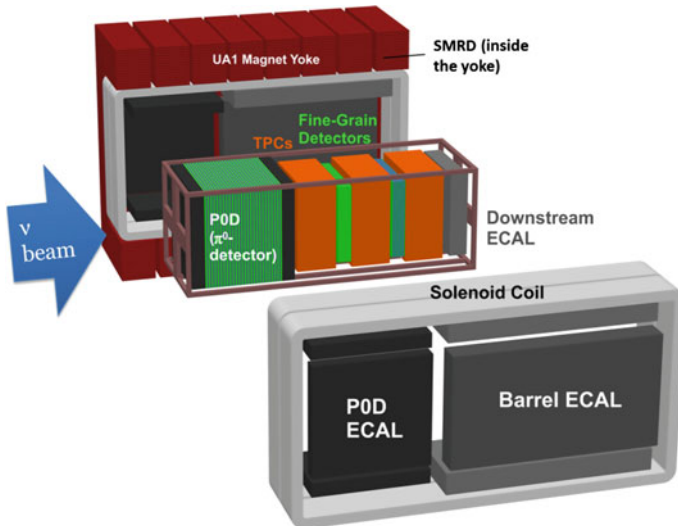


Fig. 2.12 Schematic view of ND280 detectors. In this figure, the magnet yoke and the inner detectors are drawn separately, but they are combined in the actual detector, as shown in Fig. 2.10

5.45 cm $\times$ 5.45 cm square cross sections. They are mechanically supported by the C-shaped yokes which stands on movable carriages.

- Tracker (FGD + TPC)

The tracker consists of two FGDs (Fine-Grained Detectors) [7] and three TPCs (Time Projection Chambers) [8]. These detectors are particularly important because they measure the charged current (CC) interactions, which are the signal mode for T2K.

The FGDs are made of fine-grained scintillator bars. The second FGD also contains water targets to measure the neutrino interaction on water, because the water is the neutrino interaction target in SK. The FGD provides the target mass while detecting the short-ranged particles around the interaction vertex. Detecting the short tracks in the FGD is important for identifying the neutrino interaction modes. The detail of the FGD is explained in the Chap. 3.

The long tracks, especially the leptons in the final state of the CC interaction, are detected by the TPCs. Using the TPCs, the 3-momenta of charged particles is measured from the track curvature in the magnetic field. We perform the particle identification (PID) by measuring the energy loss in the gas. The transverse momentum resolution is $\sim 10\%$, and the resolution of energy loss per length (dE/dx) is 7.8% for a minimum ionizing particle.

Figure 2.13 shows a schematic view of the TPC detector. Each of the three TPCs consists of an inner box filled with a gas mixture of Ar:CF₄:iC₄H₁₀ (95%:3%:2%). The cathode panel at the center of the inner box and the copper strips that line inside the box produces a uniform electric field in a horizontal direction aligned with the magnetic field direction, perpendicular to the beam axis. When the charged particles pass through the gas, the ionized electrons drift towards the readout plane on each side of TPCs (Fig. 2.14). The readout planes are formed from micro-mesh gaseous detectors (micromegas [9]), which amplify the electrons in a high electric field (~ 27 kV/cm) and then measure the ionization produced.

- POD (Pi-zero detector)

POD [10] locates at the upstream side of the inner magnet. It is optimized to measure the π^0 generated by neutral current interaction. The POD consists of plastic scintillators, brass sheets and water target bags. The detector can be run with the water bags filled or empty, enabling subtraction method to determine the water target cross sections.

- ECAL (Electro-magnetic CALorimeter)

ECAL [11] surrounds the Tracker and POD. The ECAL consists of the plastic scintillator layers interleaved with Pb foils. Its main purpose is to measure the γ -rays from π^0 decays which did not convert in the inner detectors. It also detects the electrons generated from the CC interaction of ν_e .

- SMRD (Side Muon Range Detector)

SMRD [12] consists of the scintillator pads which are inserted in the gaps of magnet iron yokes. The SMRD measures the range of muons from neutrino interactions that go in the side ways and missed the TPCs. It also provides the cosmic-ray triggers used for calibrating the detectors.

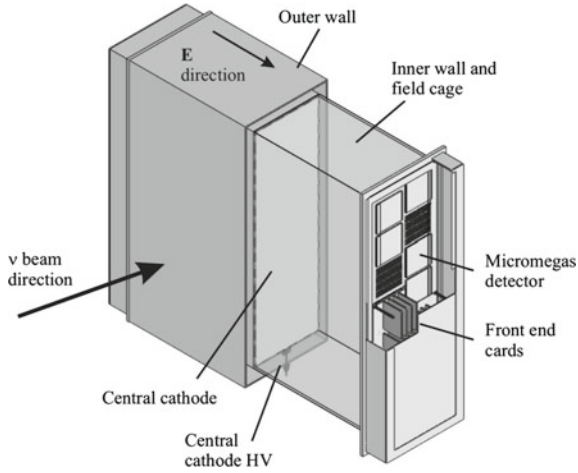


Fig. 2.13 The TPC detector [8]

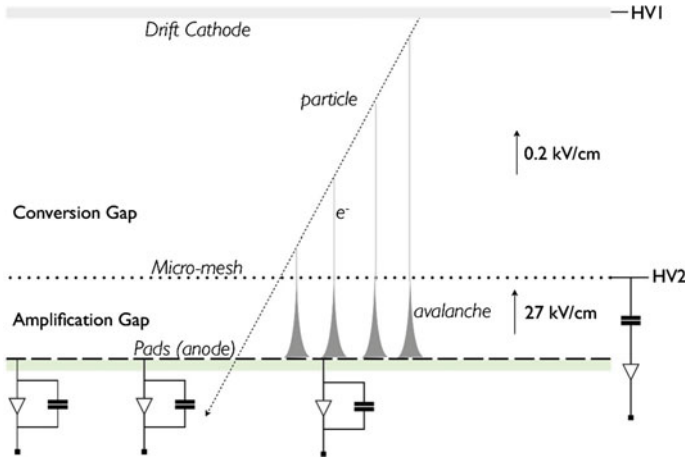


Fig. 2.14 TPC micromegas readout

All of these detectors except for the TPCs are made of plastic scintillator bars alternating with target materials such as water panel, lead foils or iron. The light from the scintillator bars are read out by the MPPCs. There are in total $\sim 50,000$ MPPCs used in ND280.

2.3.3 Far Detector (*Super-Kamiokande*)

An important feature of the T2K experiment is that we use SK, the gigantic water Cherenkov detector, for the far detector [13]. SK is 50 kton water Cherenkov detector which is located at 295 km away from J-PARC, 1000 m underground of Kamioka mine in Gifu prefecture (Fig. 2.15). The cylindrically shaped water tank is optically separated to make two concentric detectors: an inner detector (ID) and an outer detector (OD). The ID contains 11129 inward-looking 20-in. photo-multipliers (PMTs), and the OD contains 1885 outward-facing 8-in. PMTs. The ID has $\sim 40\%$ of its surface covered by the PMTs.

The charged particles above the Cherenkov threshold produces rings of light which is detected by the PMTs. It is possible to identify the particle types from the topological pattern of the light. For example, an electron produces a fuzzy ring pattern because it undergoes large multiple scattering and induce electromagnetic showers. In contrast, a muon produces sharp ring because it is resilient to changes in its momentum due to its relatively large mass.

The trigger signal is sent from J-PARC to SK via private network connection, with the information of GPS (Global Positioning System) time of the spill. The beam arrival time at SK is computed by correcting the neutrino time-of-flight and the delay of electronics. The data within $\pm 500 \mu\text{s}$ of the arrival time is recorded. The time synchronization between the J-PARC site and the Kamioka site is done by using GPS with a precision of $\sim 150 \text{ ns}$.

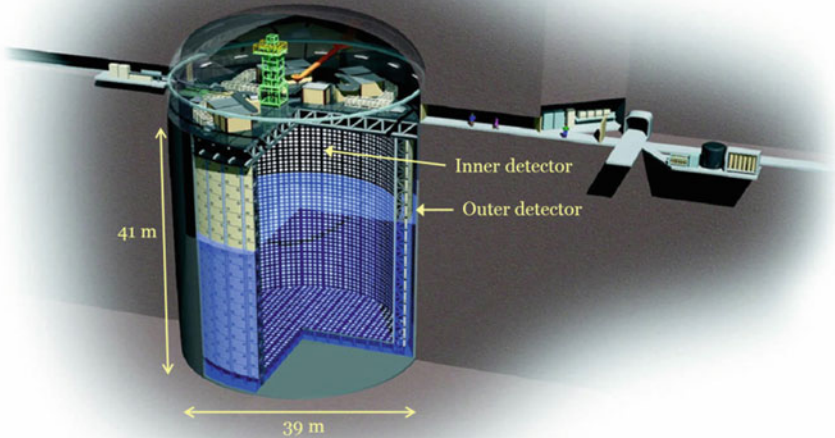


Fig. 2.15 Super Kamiokande detector

2.4 Summary of the Beam Data Taking

T2K started physics data taking in January 2010. For the analysis presented in this thesis, we use the data collected from Jan 2010 to May 2013. There are four data taking periods called Run1~4, as summarized in Table 2.2.

Figure 2.16 shows the history of the number of protons delivered to the neutrino facility. The total number of protons on target (POT) for whole run period is 6.57×10^{20} POT. The number of protons per pulse is also shown in the plot. The proton beam power is steadily increased and reached to 220 kW continuous beam operation with a world record of 1.2×10^{14} protons per pulse. We suffered from the 7.3-magnitude earthquake in Apr. 2011, but thanks to tremendous amount of work mainly by people in the J-PARC/KEK group, we restarted the beam operation in one year.

Figure 2.17 shows the stability of the neutrino event rate per POT at INGRID, and the stability of the beam direction measured by INGRID and MUMON. The neutrino event rate per POT is stable within 0.7 %, except for the period in the beginning of Run 3. The nominal value of horn current is 250 kA, while it was 205 kA in the beginning of Run 3 because of the trouble in the horn power supply. The stability of the beam direction is much better than the requirement (1 mrad) during whole run period.

Table 2.2 Summary of data taking periods

Run	Period	POT
Run 1	Jan. 2010–Jun. 2010	0.32×10^{20}
Run 2	Nov. 2010–Mar. 2011	1.11×10^{20}
Run 3	Mar. 2012–Jun. 2012	1.58×10^{20}
Run 4	Oct. 2012–May 2013	3.56×10^{20}

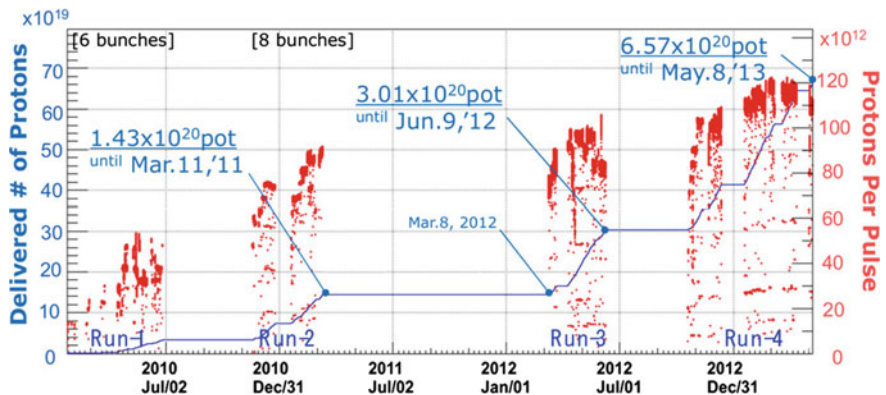


Fig. 2.16 Delivered POT to neutrino facility

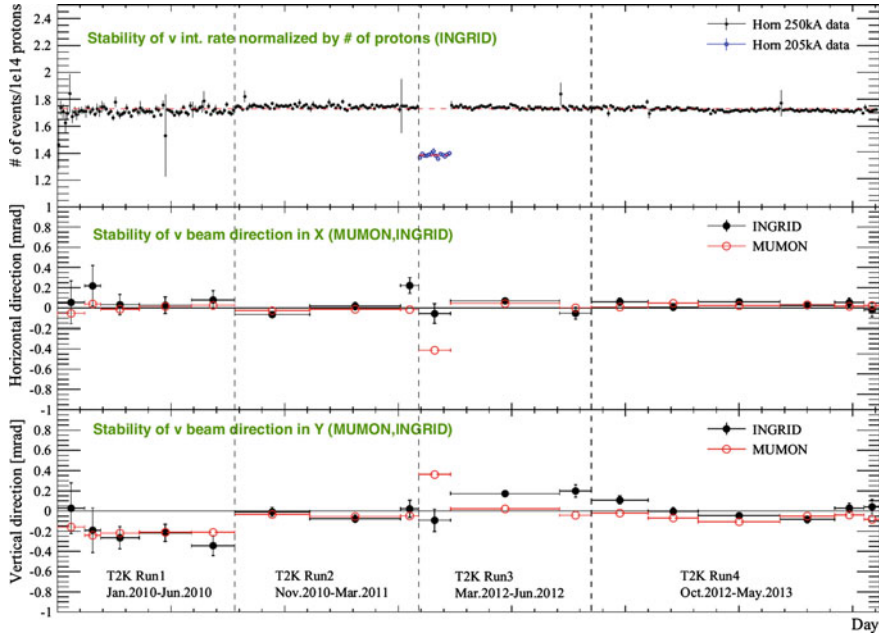


Fig. 2.17 Stability of neutrino event rate normalized by POT in INGRID (*top*), and the stability of neutrino beam direction measured by INGRID and MUMON (*middle, bottom*)

The first result from the T2K ν_e appearance measurement [14] was reported in 2011. The data sets for that analysis was Run 1 and 2 (1.43×10^{20} POT). There were six ν_e candidate events observed, and the significance was 2.5σ . For the second result which we reported in 2012 [15], we used the data sets from Run 1 to 3 (3.01×10^{20} POT), and there were 11 ν_e candidate events observed. The significance was 3.1σ . For the analysis we present in this thesis, the total POT in our data set is increased to 6.57×10^{20} POT, which is ~ 2.2 times larger compared to the previous report, and $\sim 8.4\%$ of the T2K goal. The expected significance is above 5σ .

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