Abstract. After a 3-year construction period and a commissioning phase at the end of 2009, the T2K Time Projection Chambers (TPCs) have been operated successfully during the first physics run that took place in 2010 at the J-PARC neutrino facility. This talk presents the main performance achieved by the T2K TPCs in the course of their first year of operation.

1. Introduction
The T2K Time Projection Chambers (TPCs), as part of the Near Detector (ND280) Tracker, are key elements of the experiment. The ND280 Tracker plays indeed an important role in the characterization of the neutrino beam before oscillation. Since a sizeable fraction (∼40%) of neutrino interactions at the 700 MeV peak energy are Charged Current Quasi Elastic ones (νµ + n → p + µ−), the ND280 Tracker provides precise information about the energy spectrum of the neutrino beam through the measurement of the charged lepton momentum vector. The particle identification capability of the Tracker allows also the νe contamination in the beam to be determined giving thus essential information on the irreducible background for the νµ → νe search[1].

The required performance of the T2K TPCs are a dE/dx resolution better than 10% for a good e− − µ separation, a relative momentum resolution better than 10% at 1 GeV/c and an absolute momentum scale known to better than 2%. The latter requirement is particularly important for the ∆m23 parameter measurement in the νµ disappearance channel.

The following sections give a brief description of the T2K TPCs and present their main performance. More detailed information can be found elsewhere[2].

2. The T2K Time Projection Chambers
The ND280 Tracker is made of three TPCs interleaved with two scintillator-based Fine Grained Detectors which are used as active targets. It is surrounded by the former UA1/Nomad magnet which produces a horizontal magnetic field of 0.2 T. Each TPC has a rectangular shape and is made of an inner drift volume surrounded by an external box connected to ground (Fig. 1). The inner box is divided into two parts by a central cathode maintained at a voltage of -25 kV. Each end of the inner box contains an ensemble of twelve Micro Pattern Gaseous Detectors (MPGDs) based on the bulk micromegas technology[3]. This ensemble of detectors forms a plane parallel to the cathode. The drift E-field, along the magnetic field direction, is shaped by copper strips located on the inner and outer faces of the inner box. The active tracking length in each TPC is
720 mm along the beam direction while the maximum drift distance on each side of the cathode is 897 mm. In order to minimize E-field distortions, the central cathode was built with a flatness to about 0.1 mm, and the frame that houses the MPGDs, with a planarity to about 0.2 mm.

The drift and amplification regions are filled with an Ar(95%)/CF₄(3%)/iC₄H₁₀(2%) gas mixture while the gap between the inner and outer volumes is filled with CO₂ for electrical insulation purposes. Spacers behind the micromegas detector planes are used for services: cooling, readout electronics, high-voltage (HV) and low-voltage (LV) connections, temperature probes and calibration system. The outer dimensions of each TPC are approximately 2.3 m × 2.4 m × 1 m.

2.1. Bulk micromegas detectors

The MPGDs which are used as charge amplification devices are based on the bulk micromegas technology. This technique allows large detection areas to be built and combines detector robustness and operation reliability. Each of the 72 detectors or modules instrumenting the three TPCs has dimensions of 36 × 35 cm² and contains 1726 active pads of 9.7 × 6.9 mm² area. The amplification gap between the conductive mesh and the grounded anode pad plane is 128 µm.

The choice of Ar(95%)/CF₄(3%)/iC₄H₁₀(2%) as gaseous medium for the TPCs allows sufficiently high gains to be obtained at low operation voltage (~1500 at -350V). This gas mixture has a small transverse diffusion coefficient and the maximum drift velocity for electrons is 7.8 cm/µs, almost saturated at the operation drift field of 279 V/cm. Moreover, electron attachment in the gas is small and good space-point resolution can be obtained with pads of several mm² area.

Given the rather large size of one module, a uniform response at the level of a few percent over the entire detection surface is desirable. In the case of the T2K TPCs, the rms value for the dispersion of the collected charge on a single module is typically 3%. The energy resolution at 5.9 keV, measured with a ⁵⁵Fe source, is about 8%, almost independent on the illumination.
point. Over the 72 modules instrumenting the three TPCs, the rms values for the dispersions of the average gain and resolution per module are 8% and 3%, respectively.

The TPCs are operated with a drift-to-amplification E-field ratio of about 100 allowing maximum electron transparency between the drift and amplification regions to be reached. Finally, cross-talk between neighbouring pads is typically 1%, mainly due to parasitic a capacitance from the routing strips inside the detector printed circuit board. A picture of a bulk micromegas detector mounted on its stiffening frame is shown in Fig. 2.

![Figure 2. A bulk micromegas detector for the T2K TPC.](image)

2.2. Readout electronics

The readout electronics has to cope with a total of 124,416 channels for the three TPCs. The Front End Electronics (FEE)[4] has a modular structure with six Front End Cards (FECs) and one Front End Mezzanine (FEM) mounted at the back of each micromegas detector. The readout system is based on an ASIC chip called AFTER[5]. Each AFTER chip reads 72 channels and has 511 analog memory cells provided by a switched capacitor array. The AFTER ASIC combines important features like programmable maximum charge in the 120 to 600 fC ranges, signal peaking time from 0.1 to 2 µs and a sampling frequency up to 100 MHz.

Each FEC houses four AFTER chips and their associated ADCs. The FEM board is used to collect the data from the six FECs. It also performs zero-suppression as well as slow-control functions. The data from the 72 FEM boards are collected by 18 Data Concentrator Cards[6] and are then sent to the data acquisition system (DAQ). A picture of TPC modules, instrumented with their FEE, associated shielding and cooling system, is shown in Fig. 3.

2.3. Calibration system

Two small micromegas chambers are used in the experiment to monitor the supply and return gas of the TPCs. Each of these monitoring chambers is operated with one 55Fe source to control the gas gain, and with two 90Sr sources, positioned at precisely known locations inside the chambers, to measure the drift velocity. In addition, a laser calibration system that is continuously running during data taking periods allows E-field and B-field distortions, detector gain variations as well as electron drift velocity to be studied. This calibration system consists of well-defined patterns of thin aluminum discs and strips glued on the cathode, illuminated by an external UV 266 nm (ND-YAG) laser through a set of optical fibers.
3. TPC operation

All 3 TPCS of the ND280 Tracker were operational during the first T2K physics run which took place between January and June 2010. The ND280 magnet provided a B-field intensity of 0.188 T. The drift E-field inside the TPCs was set to 279 V/cm and the bulk micromegas modules were operated at the nominal mesh voltage of -350 V corresponding to a gas gain of about 1500. The latter was found to be stable within 1% after correcting for temperature and atmospheric pressure variations which accounted for the largest part of the gain changes. At this gas gain, the average spark rate per module was measured to be below 0.1 per hour, inducing thus negligible detection dead time.

The stability of the gas mixture was found to be better than 0.01% for each of the three gas components while impurities of O₂, H₂O and CO₂ were measured to be below 2 ppm, 5 ppm and 120 ppm, respectively. By looking at charge variations of track clusters as a function of drift distance, no evidence for electron attachment was found. The micromegas detectors gave stable and uniform responses except for two modules which showed significantly lower average charge collection due to faulty HV filters.

The FEE electronics were operated with the following parameters of the AFTER chip: a charge measurement range from 0 to 120 fC, a peaking time of 200 ns and a sampling frequency of 25 MHz. The electronic noise was measured to be about 800 e⁻ corresponding to a signal to noise ratio of about 100 for minimum ionizing particles. The total power dissipation in the FEE and the LV cables amounted to 2.8 kW for the three TPCs. The temperature at the level of
the FEE and near the gas input to the TPC inner volumes was found to be stable within the 24-26°C and 20-22°C ranges, respectively.

After a zero-suppression by a factor of about 1900, the average size of beam and cosmic-ray events was typically 60 kB. Pedestal and laser events were continuously recorded during data taking for noise and calibration purposes. The TPC to DAQ throughput at the nominal 20 Hz trigger rate was below 2 MB/s.

An event display of a neutrino interaction in the ND280 Tracker is shown in Fig. 4.

![Event Display](image.jpg)

**Figure 4.** Example of an event reconstructed in the ND280 Tracker. The track crossing the first two TPCs (top left) is due to a neutrino interaction in front of the Tracker. A second more complex neutrino interaction (deep inelastic scattering) occurs in the first Fine Grained Detector with production of charged particles detected in all three TPCs.

### 4. TPC performance

#### 4.1. Spatial resolution

Space point resolution has been investigated for tracks reconstructed inside each single TPC. A track is defined by an ensemble of charge clusters formed by neighboring pads, within a column for roughly horizontal tracks, or within a row for vertical ones. The track parameters and the ionization width are then determined by maximizing the likelihood of the observed charge sharing between pads. A typical value of 247 µm/√cm for the transverse diffusion coefficient was obtained for B=0.188 T, to be compared with 288 µm/√cm when the magnet was off. These values are known, however, to be underestimated by about 10% [7].

To determine the space-point resolution, the transverse coordinate from the track fit is compared with the result from a single cluster fit. For the single cluster fit, all other track parameters were fixed. Fig. 5 shows the variation of the spatial resolution as a function of drift distance. For drift lengths above 150 mm, the resolution is below 0.8 mm but increases above 1 mm at short distances. Such a behaviour is mainly due to contributions from 1-pad clusters which are more likely to be present on a track located near the anode plane.
The variation of the spatial resolution as a function of $\tan(\phi)$, where $\phi$ is the track angle in the vertical plane, is presented in Fig. 6. A strong dependence on angle due to the ionization fluctuations along the track is observed owing to the fact that the variance of charge sharing in a cluster increases when tracks have an angle with respect to pad boundaries. This variation is well reproduced by a Monte Carlo simulation that incorporates most of the important detector effects, including transverse and longitudinal diffusion as well as a parametrization of the electronics response.

**Figure 5.** Spatial resolution as a function of drift distance. The rise at low drift distances is due to 1-pad cluster contributions.

**Figure 6.** Spatial resolution as a function of $\tan(\phi)$ where $\phi$ is the track angle in the vertical plane.

### 4.2. Field distortions

Distortions in the electron drift due to non-homogeneous and misaligned electric and magnetic fields can affect the quality of the reconstructed track parameters. Such effects can be precisely determined using laser calibration data.

E-field distortions are obtained when the ND280 magnet is turned off by comparing the measured position offsets of the aluminum discs on the cathode with respect to survey. Although work is still in progress, present measurements indicate that the displacement rms values do not exceed the space-point resolution.

B-field distortions have been investigated using laser calibration data collected with and without magnetic field. Offsets are found to be typically below 1 mm but can reach as much as 5 mm in some regions of the most downstream TPC where field non-homogeneities are stronger.

### 4.3. Momentum resolution

The track momentum resolution obtained for a single TPC was estimated with a Monte Carlo sample of muons obtained from simulated neutrino interactions. Fig. 7 shows the relative resolution of the transverse momentum component with respect to the B-field direction. The result from the simulation indicates that for transverse momenta above 400 MeV/c, the momentum resolution goal of 0.1 $p_T$ [GeV/c] is achieved.
4.4. Particle Identification

Particle identification (PID) in the TPCs is performed through dE/dx measurement. To determine the energy loss, a truncated mean method is used. For each cluster belonging to a track, the linear charge density is estimated after taking into account corrections for temperature and pressure variations. The mean energy loss \( C_T \) is then computed by keeping only 70% of the clusters corresponding to the lowest charge density values. This choice allows fluctuations from the high-energy loss tails to be minimized, improving thus the resolution on the dE/dx measurement. For minimum ionizing particles with momenta between 0.4 and 0.5 GeV/c, the relative dE/dx resolution is found to be 7.8%, better than the design goal of 10%.

Particle identification is then performed by computing the “pull” variable \( \delta_E(i) \) for each particle hypothesis \( i = e, \mu, \pi, K, p \):

\[
\delta_E(i) = \frac{C_T - C_E}{\sigma(i)}
\]

where \( C_E \) is the expected energy loss value and \( \sigma(i) \) the associated uncertainty. As an example of the PID capability of the T2K TPCs, a \(-1 < \delta_E(e) < 2\) cut applied to a sample of through-going muons with momenta below 1 GeV/c gives only a 0.2% probability of identifying particles as electrons.

The measured energy loss distributions as a function of particle momentum for through-going muons and neutrino interaction in the ND280 detector are shown in Figs. 8 and 9 for negative and positive tracks, respectively. The data are well reproduced by the expected mean energy.
loss curves for different particle types. For negatively charged tracks, most tracks are identified as muons or electrons while for positive tracks, protons, pions and positrons are clearly observed.

Figure 8. Energy loss distribution as a function of momentum for negative tracks. Figure 9. Energy loss distribution as a function of momentum for positive tracks.

5. Conclusion
Since January 2010, the T2K Time Projection Chambers have been successfully taking data. They are performing as expected and first studies indicate that the design requirements are met. More detailed analyses to better understand their performance are in progress. The TPCs have demonstrated to provide an essential contribution to the T2K physics programme.

References
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