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A TPC for the near detector at T2K

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Abstract. The Tokai to Kamiokande (T2K) experiment is the first of the next generation of long baseline neutrino oscillation experiments. Its aim is to measure θ_{13} and improve the measurements on θ_{23} and Δm^2_{23}. A highly pure neutrino beam is directed from the new accelerator center JPARC in Japan to SuperKamiokande. In addition to this far detector a second detector, the near detector (ND280), is constructed 280 m away from the target. The purpose of this detector is to measure the neutrino flux prior to its oscillation and to measure the poorly known neutrino interaction properties around 1 GeV. A central component of ND280 are three TPCs with Micro Pattern Gas Detector (MPGD) readout. In this article the purpose of the T2K experiment is explained and the R&D efforts for the main components of the TPC are presented.

1. Introduction

The Japan proton accelerator research complex (JPARC) [1] is an high intensity proton accelerator facility currently under construction. Fig. 1 shows the 3 accelerators of JPARC: a 400 MeV proton linac, a 3 GeV rapid cycle proton synchrotron and a 50 GeV proton synchrotron. The latter will be used to generate a ν_μ beam for a neutrino oscillation experiment, the Tokai to Kamiokande (T2K) experiment [1]. The neutrino beam is produced by hitting a graphite target with the proton beam. The pions and kaons generated in these reactions are afterwards focused to the forward direction by a system of 3 electromagnetic horns. After the horns there is a decay tunnel with a length of about 130 m in which the pions and kaons decay mostly in muon neutrinos and additional particles.

The axis of the neutrino beam is tilted by about 2 degrees away from the direction to the far detector. This off-axis configuration has the advantages that the width of the energy of the neutrino beam becomes narrow, and the peak of the neutrino beam energy can be tuned to the sensitivity towards the oscillation parameters by changing the off-axis angle. One of the main physics goals of T2K is the precise measurement of the oscillation parameters Δm^2_{23} and θ_{23} in the ν_μ disappearance channel. Taking into account the distance of about 295 km between the production target and the far detector and the current knowledge of Δm^2_{23} and θ_{23}, the oscillation maximum is expected to be around 700 MeV. Therefore, the energy of the ν_μ beam is chosen accordingly. Another important research topic for T2K is the measurement of the mixing parameter θ_{13}. Up to now only an upper limit on this parameter is available from the CHOOZ reactor experiment [2]. While these measurements were performed in the ν_e disappearance channel, T2K opens the possibility to measure θ_{13} in an appearance experiment. The main background contributions for this measurement come from misidentified γs from in π^0 decays and the intrinsic ν_e contamination of the beam (fig. 2).

For both physics goals it is not sufficient to measure only in the far detector, but a second detector, close to the production point is required. This near detector is described in the following section. A description of the far detector, SuperKamiokande (SK) can be found in [3].

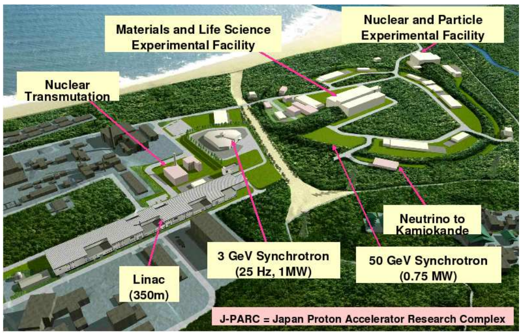

Figure 1. Accelerator complex of JPARC.

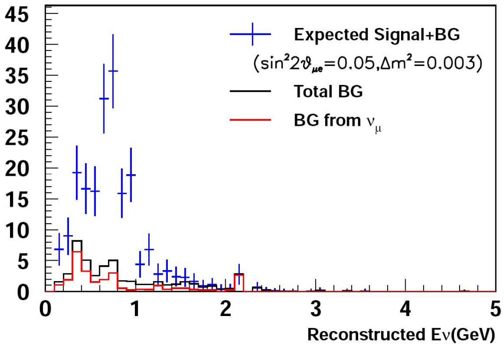

Figure 2. The ν_e appearance signal as function of the neutrino energy [4].

2. ND280

The near detector (ND280) will be located 280 m away from the target position. An artistic view of the off-axis detector is shown in fig.3. It consists of finely segmented detectors acting as neutrino targets and tracking detectors surrounded by a magnet. The purpose of the detector is to measure the neutrino spectrum, flux, ν_e contamination and interaction cross sections before the oscillation. Its main components are:

Magnet: The magnet was originally used for the UA1 experiment at CERN and is operated with a low magnetic field of 0.2 T. The inner size of the magnet is $3.5 \times 3.6 \times 7$ m^3.

SMRD: The side muon range detector (SMRD) is placed in gaps within the magnet. It consists of plastic scintillators and will measure the ranges of muons leaving the inner detectors out of the tracker acceptance. In addition it provides a cosmic ray trigger.

ECAL: The electromagnetic calorimeter (ECAL) sits inside the magnet and surrounds the inner detectors. Its main task is to measure γ-rays produced in π^0 decays. The ECAL shows a sandwich structure of scintillator bars and lead foils.

POD: The π^0 detector (POD), which is located at the upstream end of the magnet, is optimized to measure π^0s produced in neutral current reactions. These are a significant background for the ν_e appearance measurement in SK. The P0D consists of tracking planes composed of scintillating bars alternating with lead foil. Part time a water target is included to measure neutrino cross section on water.

FGD: Two Fine Grained Detectors (FGD) are located downstream from the POD. One is made of plastic scintillating bars, while for the second plastic scintillator and water bars are used alternately. On one hand the FGDs provide the target mass for neutrino interactions, on the other hand they allow to measure the direction and range of low momentum tracks produced in neutrino interactions.

TPC: Surrounding the two FGD modules three TPCs are placed to measure the momenta and the sign of the charge of particles traversing the TPCs. The momenta measurement is important to determine the energy spectrum of muons produced in charge current (CC) interactions in the FGDs. Furthermore, the dE/dx capability of the TPC allows to distinguish between electrons and muons. The design parameters of the T2K TPC is discussed in more detail in the next section.

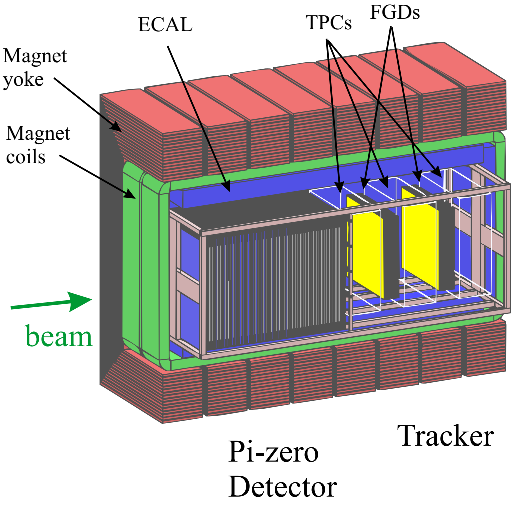

Figure 3. Artistic schematic of the ND280 detector

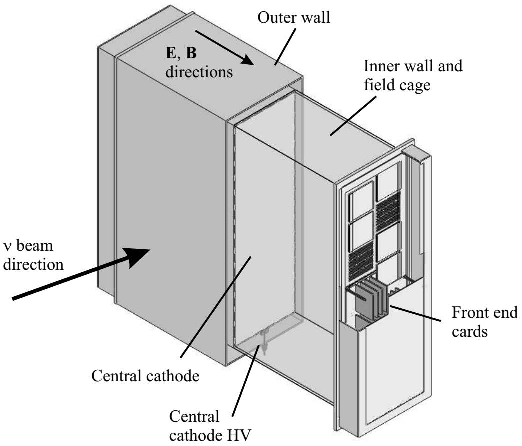

Figure 4. Design of the T2K TPC.

3. TPC Design Parameters

The tracker consisting of the FGDs and the TPCs plays a key role in the physics goals of T2K, as it provides a clean sample of charged current quasi elastic (CCQE) events. In order to do that the reconstruction of both proton and muon is required. While the former is mostly identified in the FGD, the latter is reconstructed in the TPC. The muon momentum measured by the TPC is required to determine the energy spectrum of the neutrino beam. One of the major backgrounds for the ν_e appearance measurement comes from the intrinsic ν_e contamination in the neutrino beam. The TPC will allow to distinguish between electrons and muons by measuring the dE/dx of the traversing particle. In addition the TPC will provide helpful information by measuring differential cross sections of possible background channels for the ν_μ disappearance. Finally the TPC gas itself will act as a neutrino target providing a few thousand events per year. This will help to review empirical models used in Monte Carlo simulations to describe the production of very low energetic hadrons in neutrino-nucleus reactions, since all charged particles can be measured within the TPC volume.
The requirements on the T2K TPC can be summarized as follows:

(i) The momentum resolution has to be around 10 % for 1 GeV muons which requires a good point resolution due to the very low magnetic field. Compared to other experiments this value is quite moderate, since the limiting factor in the energy reconstruction is the smearing due to the Fermi motion of the nucleon target inside the nucleus.

(ii) The energy scale has to be known at the 2 % level. This can be achieved by an excellent control of magnetic and electric field distortions and using a physical signal for the absolute momentum calibration (the invariant mass of K^0 produced in DIS neutrino events and decaying in the TPC volume). In addition this requires an extensive calibration program of the readout modules.

(iii) The dE/dx resolution has to be of the order or better than 10 % to allow a 3σ separation of electrons and muons in the interesting energy range of 0.5 to 1 GeV.

4. TPC R&D Efforts and Design

To fulfill the requirements mentioned above various R&D efforts were performed before the design was decided. In the following the design issues of the most important components of the TPC are summarized.

4.1. Field Cage

The field cage has been designed with the main criterion of robustness and simplicity of construction. In addition great importance was attached to the achievement of a very good electric field homogeneity inside the active volume. Each TPC module has a height of 2.5 m, a depth of 2.5 m and a width of around 1 m. These dimensions are given by the available space inside the magnet. For the T2K TPC the design of the STAR TPC [5] was adopted which is made of a double box structure. On the inner box field strips are coated on both sides of the wall, defining the electric field in the drift volume. The inner box has a height of about 2.3 m, a width of 0.76 m and a depth of around 2 m. The drift volume is divided by the cathode in two equally sized halves. The cathode will be loaded with aluminum strips for the laser calibration system. The outer box is separated from the inner box by a gap of 6.8 cm on the sides and top and 11.8 cm on the bottom. The surfaces of the outer box are aluminum at nominal ground potential. To guarantee the HV stability of up to 40 kV the gap between the inner and the outer box is filled with CO_2. The CO_2 also acts as a shield for gas contaminations from the atmosphere. As a difference to similar TPC designs, the electronics is contained in the gas envelope. This allows to have only a small pressure difference between the inner and the outer box avoiding a deflection of the readout plane and the field forming structures. A prototype following this design was built at TRIUMF and afterwards shipped to the University of Victoria, where it was operated successfully with a GEM readout.

4.2. Readout Modules

For the readout of the TPCs two technologies were originally under discussion: MicroMegas [6] and Gas Electron Multipliers (GEM) [7]. Both were tested extensively in a R&D program with the HARP TPC [8] at CERN and with the field cage prototype in Victoria. It turned out that both technology yielded comparable results (fig. 5). Finally it was agreed that MicroMegas are used for the readout of the TPCs.

For each readout plane of the TPC 12 MicroMegas modules are used. Each of the size of 36×34 cm^2. The pad size is 6.9×9.7 mm^2 arranged in 48 rows and 36 columns giving in total 1728 channels per module. For the production of the modules the “bulk” MicroMegas method was chosen [9] which is based on photo lithography techniques. In this way the MicroMegas modules are easy to produce in the required quantities, the dead zones between the modules are minimized and good gas gain uniformity is guaranteed. Each module will be tested and calibrated in a test-bench before installing it in the TPC [10].

4.3. Gas Choice

Important parameters for the choice of gas in the drift volume are the transverse diffusion coefficient and the achievable gain. Furthermore the sensitivity to the magnetic field, electron attachment and contaminations has to be considered. During the measurements at the HARP TPC several gas mixtures were tested. Very promising results were obtained with $Ar:CF_4:iC_4H_{10}$ 95:3:2 which is currently the baseline choice. Further optimization work about the fractions of CF_4 and isobutane are ongoing. In addition it is studied to exchange CF_4 by CO_2. This has a positive effect on the sensitivity to the magnetic field, but the influence on the gain and attachment has to be further investigated.

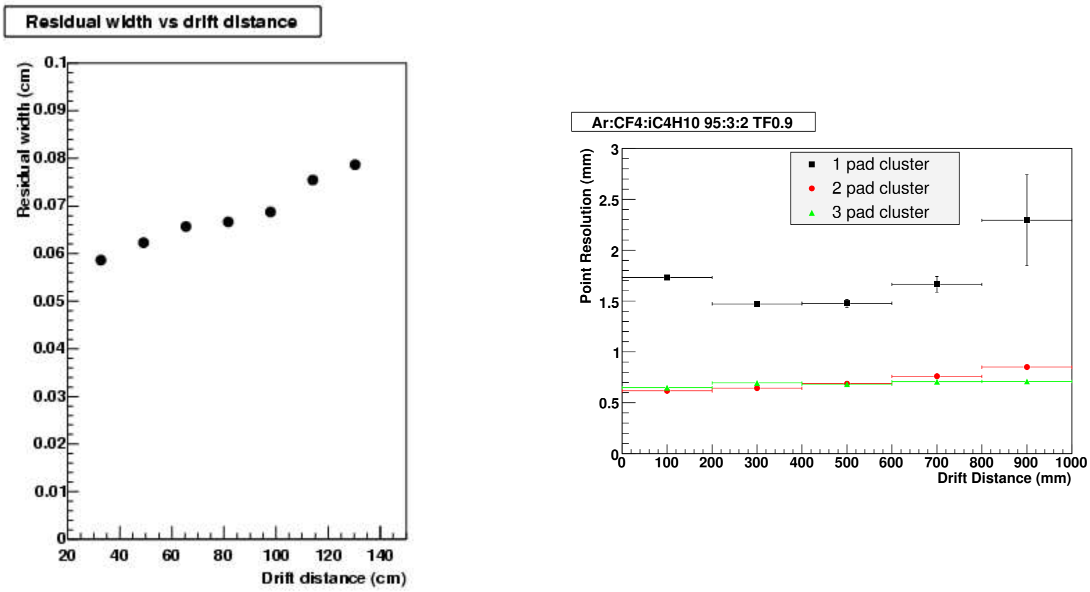

Figure 5. Point resolution as function of z: with MicroMegas readout for 2 pad clusters (left) and with GEM readout for 1, 2 and 3 pad clusters (right) [11].

4.4. Electronics

In total the three TPC modules have $\sim$ 124,000 pads. The spill rate is $\sim$ 0.3 Hz and in addition cosmic ray and laser calibration events have to be read out. Therefore the electronics is designed to read out with a rate of 20 Hz. The electronics is based on a newly developed ASIC chip based on the 0.35 μm CMOS technology. Each chip contains 72 individual channels with 511 time bins, whereby each pad will be connected to one channel. Interesting features are that both input signal polarities are supported and that both gain and peaking time are programmable. The signal to noise ratio for a MIP is expected to be $\sim$ 100. This general design of the chip allows that it can also be used for the readout of the FGDs. Four ASICs are mounted on one Front-End Card (FEC) on which the digitalization takes place. On each MicroMegas module 6 FECs will be mounted which will be connected to one Front-End Mezzanine card (FEM). The FEM performs several tasks. It receives the clock, trigger and synchronization information and duplicates these signals for the FECs. In addition it acts as a master device for programming the FECs. Also a first data compression is achieved in the FEM. The 12 FEMs of each readout plane are connected to a Data Concentrator Card (DCC) via an optical fiber. The DCC performs the final 0-suppression and sends the TPC data to the DAQ for storage at 10 MB/s.

5. Expected Performance

Monte Carlo simulations, which describes the results of the HARP test measurements very well, show that the performance goals required by the T2K physics goals will be fulfilled. Fig.7 shows the expected momentum resolution as function of the momentum of the muon for three different transverse diffusion coefficients. The dE/dx performance can be estimated by the empirical formula [12]:

$$\frac{\sigma(dE/dx)}{dE/dx} \sim 0.4n^{-0.43}(xP)^{-0.32} \tag{1}$$

Here, n is the number of samples, x the length of one sample and P the pressure. The results of the measurements are in agreement with this formula. Considering the design parameters the

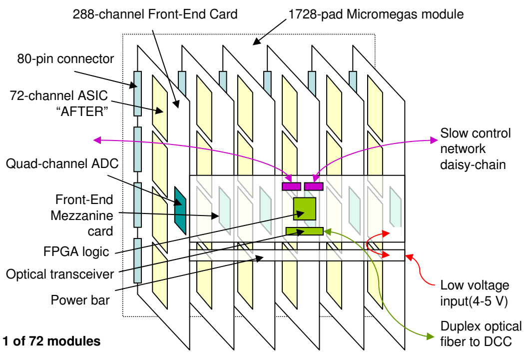

Figure 6. Readout architecture of a readout module.

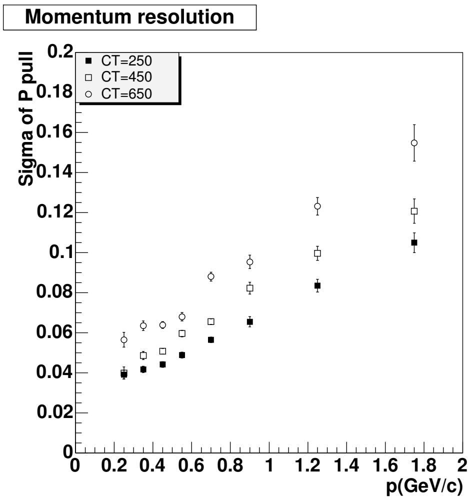

Figure 7. Momentum resolution as function of the momentum for several transverse diffusion coefficients [μm/$\sqrt{\text{cm}}$].

expected dE/dx resolution is ≈ 10% allowing a 3σ separation between electrons and muons in the interesting energy range.

6. Summary and Outlook

For the near detector of the neutrino oscillation experiment T2K a TPC was chosen as a central component. A wide range of R&D efforts were undertaken for the design of the T2K TPC. Considering the results from the measurements at CERN and in Victoria, it is expected that the T2K TPC will fulfill the physics requirements for T2K.

Currently a first full size TPC module (Module 0) is constructed with which tests under experimental conditions will be performed before the design is finalized. Afterwards the construction of the three T2K TPCs will start. The T2K TPCs will be operable when the first neutrino beam is provided by JPARC in May 2009.

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