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Time projection chambers for the T2K near detectors

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ABSTRACT

The T2K experiment is designed to study neutrino oscillation properties by directing a high intensity neutrino beam produced at J-PARC in Tokai, Japan, towards the large Super-Kamiokande detector located 295 km away, in Kamioka, Japan. The experiment includes a sophisticated near detector complex, 280 m downstream of the neutrino production target in order to measure the properties of the neutrino beam and to better understand neutrino interactions at the energy scale below a few GeV. A key element of the near detectors is the ND280 tracker, consisting of two active scintillator–bar target systems surrounded by three large time projection chambers (TPCs) for charged particle tracking. The data collected with the tracker are used to study charged current neutrino interaction rates and kinematics prior to oscillation, in order to reduce uncertainties in the oscillation measurements by the far detector. The tracker is surrounded by the former UA1/NOMAD dipole magnet and the TPCs measure the charges, momenta, and particle types of charged particles passing through them. Novel features of the TPC design include its rectangular box layout constructed from composite panels, the use of bulk micromegas detectors for gas amplification, electronics readout based on a new ASIC, and a photoelectron calibration system. This paper describes the design and construction of the TPCs, the micromegas modules, the readout electronics, the gas handling system, and shows the performance of the TPCs as deduced from measurements with particle beams, cosmic rays, and the calibration system.

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1. Introduction

Over the past decade, the phenomenon of neutrino oscillation has been firmly established from observations of neutrinos produced by cosmic rays in the atmosphere [1], by the sun [2], by nuclear reactors [3], and by accelerators [4,5]. The goals of the T2K experiment [6] are to improve the measurements of the atmospheric (2–3) mixing parameters by an order of magnitude by studying ν_μ disappearance, and to increase the sensitivity to 1–3 mixing by studying ν_e appearance, possibly observing this for the first time. If the experiment finds evidence for 1–3 mixing, this will open the possibility of measuring leptonic CP-violation in the future.

1.1. T2K and the off-axis near detector

The T2K experiment is designed with an off-axis neutrino beam configuration [7,8], providing a relatively narrow band beam peaked at about 700 MeV, so that the far detector is located at the first oscillation maximum. Near detectors, located 280 m downstream of the production target, are designed to ensure that the neutrino beam properties are well understood so that the experiment can reach its ultimate sensitivity. On the neutrino beam axis, the INGRID detector monitors the neutrino beam profile. Along the off-axis direction towards the far detector, the ND280 detector measures the interaction rates, neutrino spectra, and neutrino interaction kinematics.

The ND280 detector consists of several detector systems contained within the former UA1/NOMAD dipole magnet which provides a magnetic field of approximately 0.2 T. Innermost are the PiZero detector, specifically designed to study neutral current interactions that produce π^0 particles and a tracker, consisting of two fine-grained scintillator detectors (FGDs) that act as active neutrino targets interleaved with three time projection chambers (TPCs). Electromagnetic calorimeters surround these detectors within the magnet coil and planes of scintillators are inserted within the magnet yoke to act as a muon range detector.

1.2. ND280 tracker

The ND280 tracker is designed to study charged current neutrino interactions. At 700 MeV, a sizable fraction of neutrino interactions are charged current quasi-elastic (CCQE), in which the neutrino energy can be determined by measuring the momentum of the charged lepton. For 2–3 mixing studies, the spectrum of ν_μ interactions observed in the near detector will be used to estimate the unoscillated spectrum at the far detector, and ν_μ interaction kinematics will be studied to help model background from non-CCQE interactions in the far detector. For 1–3 mixing studies, the near detector will measure the ν_e contamination in the beam, an important and irreducible background at the far detector.

1.3. Tracking performance requirements

At 700 MeV, neutrino energy estimation in CCQE events is limited at about the 10% level due to the Fermi motion of the struck nucleons. For this reason, a relatively modest momentum resolution goal is set to be $\delta(p_\perp)/p_\perp < 0.1 p_\perp$ [GeV/c] (perpendicular to the magnetic field direction). The overall momentum scale, however, needs to be known at the level of 2%, in order not to limit the precise determination of Δm^2_{23}. The ionization energy loss of electrons in 1 atm argon gas is roughly 45% larger than for muons over the momentum range of interest. To measure the ν_e contamination of the beam, the resolution in ionization energy loss needs to be better than 10%.

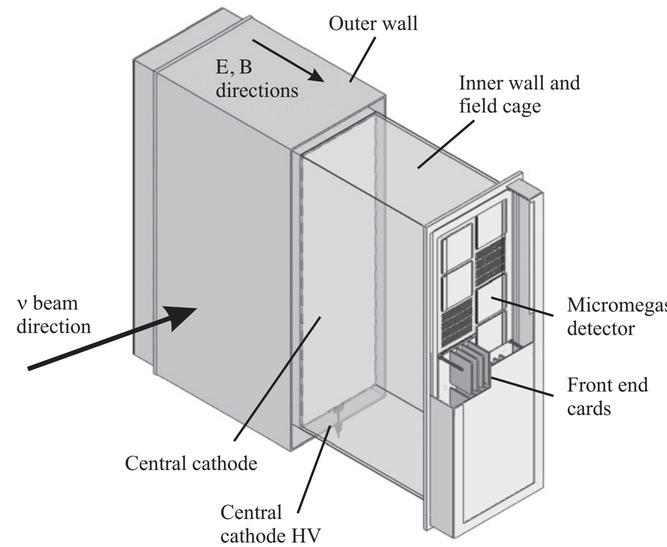

Fig. 1. Simplified cut-away drawing showing the main aspects of the TPC design. The ND280 off-axis detector uses a right handed coordinate system with z in the horizontal plane along the neutrino beam direction, and y in the vertical direction.

1.4. TPC system design overview

The tracker performance goals can be reached with time projection chambers [9] operated in a magnetic field of 0.2 T with a sampling length of 700 mm and pad segmentation of 70 mm^2, providing space point resolution of about 0.7 mm. For gas-amplified readout of the ionization electrons, the collaboration decided to use bulk micromegas detectors [10]. To fit the geometry of the UA1/NOMAD magnet, a rectangular design for the TPCs was required.

A double box design was selected, in which the walls of the inner box form the field cage, and the walls of the outer box are at ground potential, with CO_2 acting as an insulator between. The walls are made from composite panels, and the inner box panel surfaces are machined to form a copper strip pattern, in order to produce a uniform electric drift field. A simplified drawing of the TPC design is shown in Fig. 1.

The gas system is designed to maintain a stable mixture in the inner volume and a constant positive pressure with respect to the outer volume. The inner gas mixture, Ar:CF_4:i C_4H_{10} (95:3:2) referred to as "T2K TPC gas" in this document, was chosen for its high speed, low diffusion, and good performance with micromegas detectors. There are 12 micromegas modules that tile each readout plane in two offset columns, so that inactive regions are not aligned. Front-end electronics cards that plug into the back of the micromegas modules digitize buffered analog data and send zero suppressed data out of the detector with optical links. A photoelectron calibration system is incorporated into the design to generate a control pattern of photoelectrons from the cathode.

The next six sections describe these TPC subsystems in detail, followed by a report on the overall performance of the TPCs.

2. Mechanical structure

A TPC module consists of two gastight boxes, one inside the other. The inner box (Fig. 2) is subdivided by the cathode located at its midpoint, and supports the 12 micromegas modules that are located in a plane parallel to the cathode at each end. The walls joining the cathode and the micromegas are covered with a series of conducting strips joined by precision resistors, forming a voltage divider that creates the uniform electric field along