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Proceeding Paper

The T2K Near Detector Upgrade †

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Abstract: The T2K experiment is a long baseline neutrino oscillation experiment conducted in Japan. It aims to precisely measure the neutrino oscillation parameters by measuring the muon neutrino beam produced at the J-PARC accelerator complex at both near and far detectors. The magnetized T2K near detector complex ND280 plays an important role in measuring the neutrino interactions before the oscillations and constraining the systematic uncertainties in the measurements of neutrino oscillation parameters. The physics goals of T2K are to test Charge-Parity (CP) symmetry in the lepton sector, to precisely measure the neutrino oscillation parameters θ_{23} and Δm^2_{32}, and to determine the neutrino mass ordering and the octant of θ_{23}. T2K has disfavored CP conservation with a significance level of 2σ, and the higher significance level can be achieved by increasing the statistics and reducing the systematic uncertainties. Thus, the T2K collaboration proposed upgrading ND280 by replacing the P0D detector with a new fine-grained scintillator detector SuperFGD and two Time-Projection Chambers (TPCs). In addition, these new detectors will be covered by six Time Of Flight (TOF) planes. The performances of these upgrade detectors have been tested and confirmed to satisfy the requirements of the ND280 upgrade program. The physics performances of the upgraded ND280 have also been studied and they show promising improvements in neutrino interaction measurements by introducing transverse kinematics variables.

Keywords: neutrino; T2K; near detector

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1. Introduction

The T2K experiment is a long baseline neutrino oscillation experiment located in Japan. It is designed to measure the neutrinos produced at J-PARC at the off-axis near detector ND280, on-axis near detector INGRID, and the far water Cherenkov detector Super-Kamiokande located 295 km away from the neutrino production point. These settings allow for the measurement of the neutrino oscillation parameters θ_{13} and δ_{CP} through the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance channels and Δm^2_{32} and θ_{23} through the ν_μ and $\bar{\nu}_\mu$ disappearance channels. T2K has excluded CP conservation in neutrino oscillations at the 2σ significance level [1]. To achieve 3σ or higher significance on CP violation, it is important to increase the statistics and reduce the systematic uncertainties. For this purpose, upgrade projects for T2K were proposed, including an increase in beam power from 500 kW to 1.3 MW and an upgrade of the T2K near detector complex ND280. On the far detector side, Gd loading to the Super-Kamiokande and the Hyper-Kamiokande project is ongoing.

2. ND280 Upgrade Overview

2.1. Current ND280

The T2K off-axis near detector complex "ND280" is located 280 m downstream of the neutrino generation target. It has a good capability to measure the neutrino flux and cross-sections and constrain the systematic uncertainties in the oscillation analysis. ND280 consists of two types of tracking detectors, Fine-Grained Detectors (FGDs) and Time-Projection Chambers (TPCs), surrounded by Electromagnetic Calorimeters (ECals) and Side Muon Range Detectors (SMRDs), as shown in Figure 1. FGDs are the main neutrino interaction targets. FGD1 consists of scintillators and FGD2 consists of scintillators and water targets. Three TPCs filled mainly with Ar gas provide particle identification (PID) based on the energy loss and momentum measurements. These detectors are placed in a 0.2 T horizontal dipole magnetic field so that they can provide charge identification of outcoming leptons, which is crucial for identifying the neutrino types. ND280 has played a key role in measuring the cross-sections of various channels, neutrino types, and target materials [2,3].

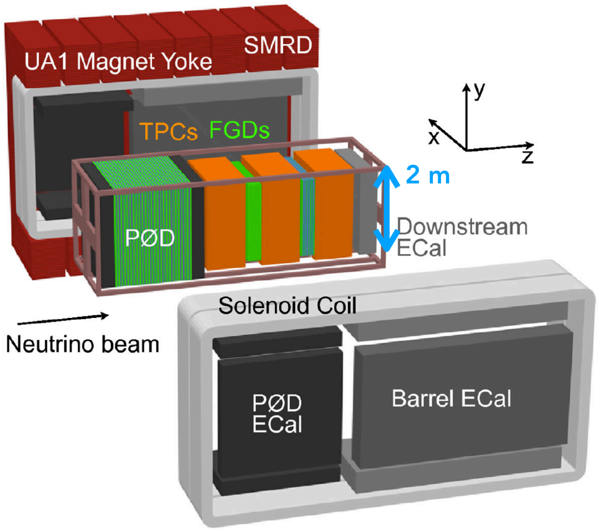


Figure 1. Schematic view of ND280.

2.2. Motivation for ND280 Upgrade

There are some potential weaknesses in the current ND280. It has a relatively limited acceptance for particles with a large scattering angle since TPCs are only located downstream of FGDs and FGDs consist of scintillator bars perpendicular to the beam direction. In addition, since FGDs require particles to pass more than three layers to be reconstructed and short protons cannot be reconstructed, the detection threshold for protons is higher than the peak energy of protons in the T2K energy range. It also has no neutron information and poor electron/photon separation for the ν_e measurements. To further reduce the systematic uncertainties for future oscillation analyses, it is expected to cover these weaknesses with the ND280 upgrade.

2.3. New Detectors for the ND280 Upgrade

The Pi-0 Detector (P0D) will be replaced with new 4π acceptance detectors, as shown in Figure 2. The main target detector is the Super Fine-Grained Detector (SuperFGD). It is a fully active plastic scintillator detector. The SuperFGD will be vertically sandwiched by two High-Angle Time-Projection Chambers (HA-TPCs) that enable the high-resolution tracking of charged particles exiting from the SuperFGD. These SuperFGD and HA-TPCs will be surrounded by six Time Of Flight detectors (TOFs) that will provide time information to reject background events. In the following sections, we will describe the construction status and the results of the performance tests of each detector in more detail. Detailed descriptions of these new detectors are also reported in [4].

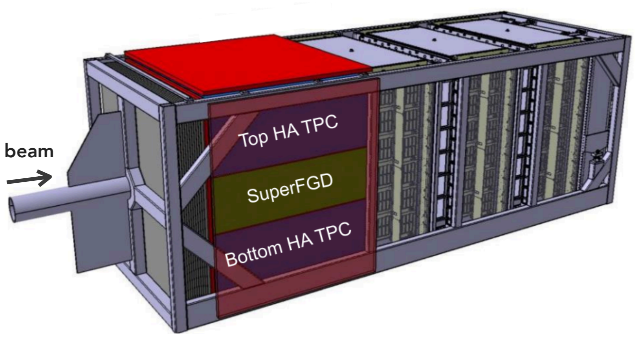


Figure 2. Schematic view of upgraded ND280.

3. SuperFGD

The SuperFGD is a fully active plastic scintillator detector consisting of 2.1 million plastic scintillator cubes with a size of $\sim$1 cm^3. It has a target mass of 2.2 tons. Scintillation light is read out through wave-length shifting (WLS) fibers in three orthogonal directions and detected by Multi Pixel Photon Counters (MPPC), as shown in Figure 3.

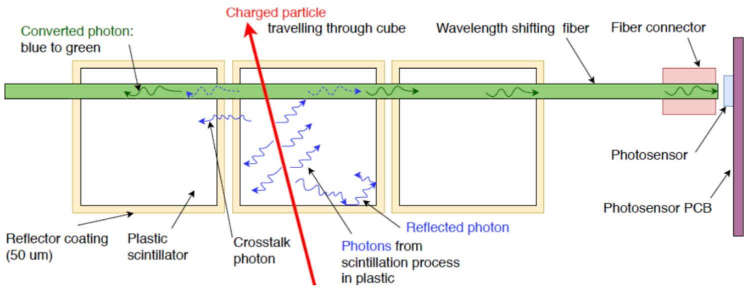


Figure 3. Readout mechanism of SuperFGD.

Compared with the current FGDs, the SuperFGD is expected to have better neutrino interaction measurement capabilities, such as 3-dimensional tracking and reconstruction, and a lower energy threshold for protons (500$\rightarrow$350 MeV/c). It also can measure the neutron kinematics using Time of Flight [5] and has better electron/photon separation capabilities.

3.1. Construction Status

All the cubes have been produced at INR and delivered to J-PARC. All 57,000 WLS fibers have been produced and they will be inserted into the cube holes. The mechanical box needs to be able to withstand 2 tons of weight and earthquakes and its design has been validated with prototypes. The design of the readout front-end electronics is now finished and 400 MHz samplings will provide 2.5 ns timing information. An integrated calibration system for regular MPPC calibration is also being constructed.

3.2. Performance Test

For the performance test of the SuperFGD, beam tests have been performed several times using prototypes at CERN and LANL. The results of the charged-particle test beam at CERN [6] and neutron test beam at LANL [7] have been published, respectively. The measured charged distributions show a clear separation of protons and muons as shown in Figure 4.

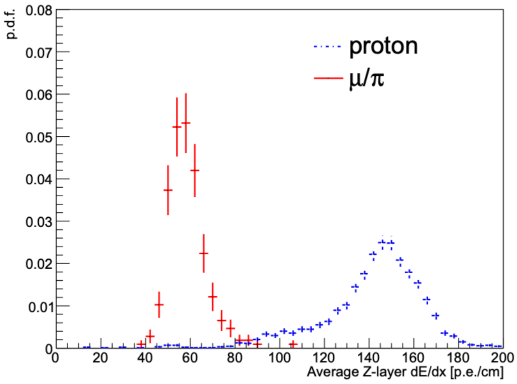
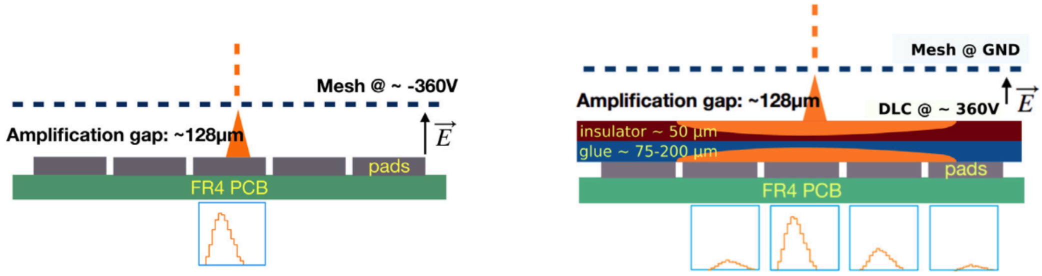


Figure 4. Measured charge distributions for protons and muons/pions (MIPs) at the beam test [6].

4. High-Angle Time-Projection Chambers (HA-TPCs)

In the ND280 upgrade, two HA-TPCs will be introduced so that they can provide tracking and particle identifications. They have dimensions of 1.865 × 2.0 × 0.82 m^3 and are filled with the same T2K gas (Ar:CF_4:¡ C_4H_{10} = 95:3:2). The Bulk Micromegas readout module that was used in the current TPCs will be replaced by new resistive Micromegas Modules (ERAMs). They spread the charge over multiple pads, improving the spatial resolution and reducing the number of readout pads, as shown in Figure 5.



(**a**) Bulk Micromegas Module (**b**) Resistive Micromegas Module

Figure 5. Schematic view of two types of Micromegas Modules [8].

Performance Test

The performance test of HA-TPC prototypes was conducted using the test beams at DESY and CERN [8,9]. It was confirmed that it fulfills the spatial resolutions < 0.8 mm for all angles and dE/dx resolution < 10%, which fully satisfies the requirements for the ND280 upgrade. New reconstruction algorithms are being developed based on these test beam data.

5. Time of Flight Detectors (TOFs)

In the upgrade configurations, six TOF planes will cover two HA-TPCs and the SuperFGD. Each plane (2.2 × 2.4 m^2) consists of 20 scintillator bars. The scintillation light will be read out with 16 MPPCs at both ends of each bar. TOFs will provide a time stamp for each track to identify its direction and reduce the background. In addition, the cosmic trigger for the calibration of the SuperFGD and HA-TPCs will be available using the time information of the TOFs.

Performance Test

The performance test was performed using the cosmic muons and the average double-sided time resolution of one bar was measured to be 0.14 ns, as shown in Figure 6 [10]. This satisfies the requirements of the ND280 upgrade.

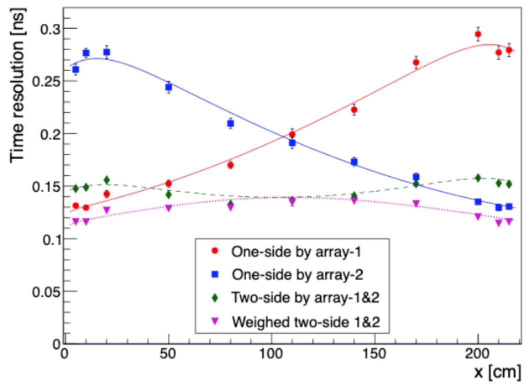


Figure 6. Measured time resolution of TOFs [10].

6. Physics Performances

The upgrade of ND280 allows us to have better efficiency for the 4π phase space, which is similar to the far-detector, as shown in Figure 7. The fine granularity of the SuperFGD provides 3D tracking for both lepton and hadrons and, thus, we can access transverse variables. By taking full advantage of this, we will have a better understanding of the nucleon's final state interaction (FSI) and other nuclear effects. The expected physics sensitivity using the upgraded detectors was studied by adding new transverse variables δp_T, $\delta\alpha_T$, and E_{vis}, as shown in Figure 8 [11]. It allows for a constraint on the one-particle one-hall (1p1h) process as good as 1.5% (2%) in ν ($\bar{\nu}$) interactions, while for the n-particle n-hall (npnh) process, it allows for a constraint better than 5% (10%) in ν ($\bar{\nu}$) interactions. In these plots, 1p1h includes charged current quasi-elastic (CCQE) interactions without the short-range correlation (SRC), and npnh includes 2p2h and CCQE with SRCs.

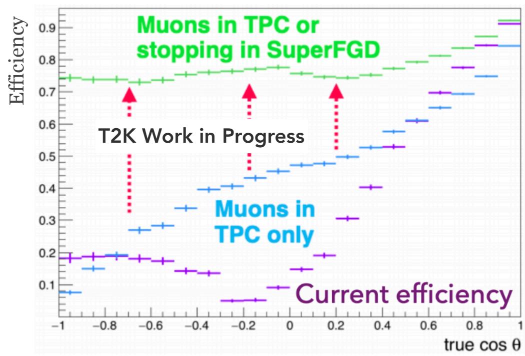
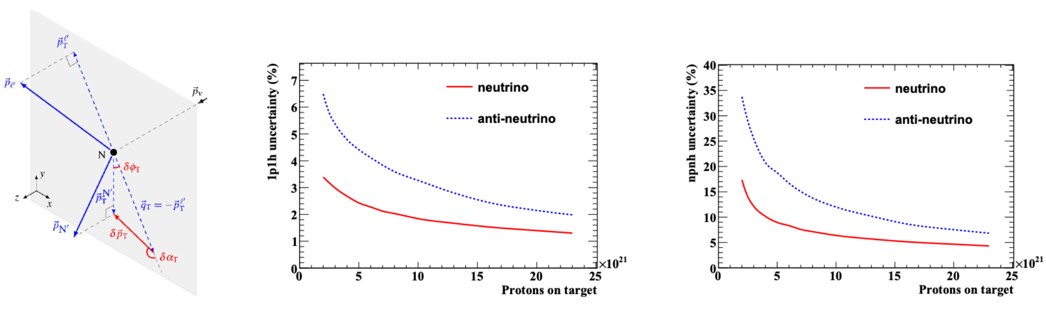


Figure 7. Comparison of muon detection efficiencies with the current and upgraded ND280.



(**a**) (**b**) (**c**)

Figure 8. Physics performance studies of ND280 upgrade [11]. (**a**) Transverse variables, (**b**) uncertainties in 1p1h interaction as a function of POT, (**c**) uncertainties in npnh interaction as a function of POT.

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