PROCEEDINGS OF SCIENCE

T2K upgrades: near detector and beam

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The T2K experiment is a second-generation long-baseline neutrino oscillation study aimed at exploring physics beyond the Standard Model. It uses an off-axis neutrino beam with a peak energy of around 0.6 GeV, produced at the J-PARC accelerator to investigate neutrino and antineutrino oscillations. The ND280 near detector, located at J-PARC, helps minimize systematic uncertainties related to neutrino flux and interactions. Recently, both the ND280 and the neutrino beamline underwent upgrades, enabling stable operation at 800 kW with a 10% increase in neutrino flux. The ND280 upgrade includes a high-granularity target with 2 million optically isolated scintillating cubes, two horizontal time projection chambers (TPCs) with resistive Micromegas, and six panels of scintillating bars for precise time-of-flight measurements. These enhancements, installed in 2023-2024, are vital for improving the measurement of CP violation in the leptonic sector, aiming for greater than 3σ significance in the second phase of T2K.

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1. Introduction

T2K [1] is a second-generation long-baseline neutrino oscillation experiment in Japan designed to study neutrino oscillations using a ν_μ ($\bar{\nu}_\mu$) beam. The neutrino beam is generated at J-PARC in Tōkai and is first detected 280 meters downstream at the near detector complex, where oscillations have not yet altered the flavor composition. The beam then travels 295 km to the Super-Kamiokande (SK) far detector [2, 3] in Hida, where oscillations significantly impact the flavor composition (Fig. 1). The near detector complex includes two detectors: INGRID [4], located on the beam axis, monitors the neutrino beam's flux and direction, while ND280 [5], positioned 2.5 degrees off-axis, studies the unoscillated neutrino spectrum and interaction cross-sections. The SK far detector, also 2.5 degrees off-axis, is a 50-kton water Cherenkov detector exposed to a narrow-band neutrino flux peaking at 0.6 GeV, the oscillation maximum.

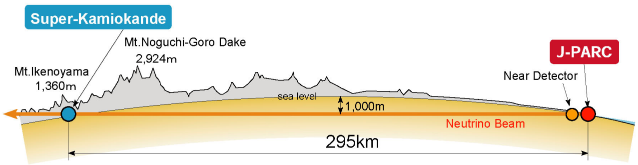

Figure 1: Schematic view of T2K experimental setup.

2. Motivations behind beam and ND280 upgrades

T2K's sensitivity to neutrino oscillations and the measurement of δ_{CP}[1] can be enhanced by increasing statistics and reducing key systematic uncertainties. Upgrading the neutrino beam is critical to achieving the statistical increase (20×10^{21} POT) needed to measure CP violation in the leptonic sector with a significance greater than 3 sigma [8, 9]. Improved precision in δ_{CP} and oscillation measurements requires addressing the largest systematic uncertainty, which stems from limited knowledge of neutrino-nucleus interactions in the sub-GeV energy range. To tackle this, accurate neutrino cross-section models are necessary, alongside upgrades to the ND280 detector. These upgrades expand the detector's phase space, improving access to interactions with high-angle or backward-going lepton production, aligning with Super-Kamiokande's capabilities. The previous ND280 configuration had limitations, including a high momentum threshold (450 MeV/c), low proton reconstruction efficiency, and no ability to reconstruct neutrons, critical for understanding neutrino-nucleus interactions and accurately determining incident neutrino energy in oscillation studies.

3. Neutrino beam upgrade

Neutrinos are generated from decayed pions or other particles produced in proton-graphite target interactions. The KEK/J-PARC Center upgraded the J-PARC main ring accelerator to

[1] The Pontecorvo-Maki-Nakagawa-Sakata mixing matrix CP violating phase [6, 7].

increase the repetition rate of the proton beam from 2.48 to 1.36 seconds, boosting proton supply to the neutrino production target. The T2K collaboration also enhanced components of the neutrino beam facility, including targets, electromagnetic horns, and beam monitors. Beam commissioning began in November 2023, achieving stable neutrino beam production at record power levels: 760 kW in December 2023 (50% higher than pre-upgrade) and 800 kW by June 2024, exceeding the initial design. The goal is to reach 1.3 MW by 2027, coinciding with the start of Hyper-Kamiokande [10] operations. Upgraded electromagnetic horns now operate at 320 kA (previously 250 kA), improving pion focusing efficiency and increasing neutrino observations by 10%, while delivering higher-quality beams to the Super-Kamiokande detector.

4. ND280 upgrade

The ND280 upgrade [11] was installed in the section previously occupied by the π^0 detector called P0D (Fig. 2). The upgraded part of ND280 consists of: a high-granularity scintillator target capable of reconstructing low-momentum particles, called the Super-Fine Grained Detector (Super-FGD); two new horizontal Time Projection Chambers (TPCs), referred to as High Angle TPCs (HA-TPCs), positioned above and below the Super-FGD to detect high-angle charged particles produced in neutrino interactions with the Super-FGD. Finally, six Time-of-Flight (ToF) modules surround the Super-FGD and the two HATPCs to veto particles generated outside the fiducial volume of ND280. The entire ND280 upgrade was successfully installed in the spring of 2024 and collected data during the summer of 2024.

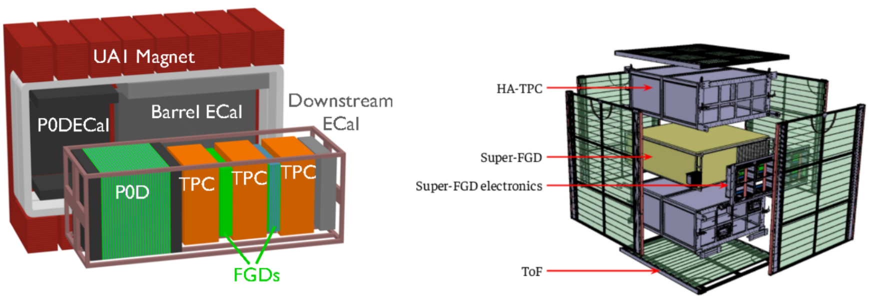

Figure 2: A schematic of the original ND280 design (left), and the suite of new detectors included in the ND280 upgrade(right).

4.1 Super-FGD

The Super-FGD [12] is a 2-ton scintillator target comprising ~2 million optically isolated cubes of 1 cm^3 (Fig. 3). Scintillation light generated in the cubes is collected using three wavelength-shifting (WLS) fibers oriented in mutually perpendicular directions, with each fiber connected to a Hamamatsu Multi-Pixel Photon Counter (MPPC). This design enhances ND280 by increasing target mass, lowering the proton detection threshold to ~300 MeV/c, improving spatial resolution for short particle tracks, and enabling neutron reconstruction crucial for antineutrino charged-current quasielastic (CCQE) and two-particle-two-hole (2p2h) interactions [13–19] studies. It also offers precise energy deposition and timing measurements.

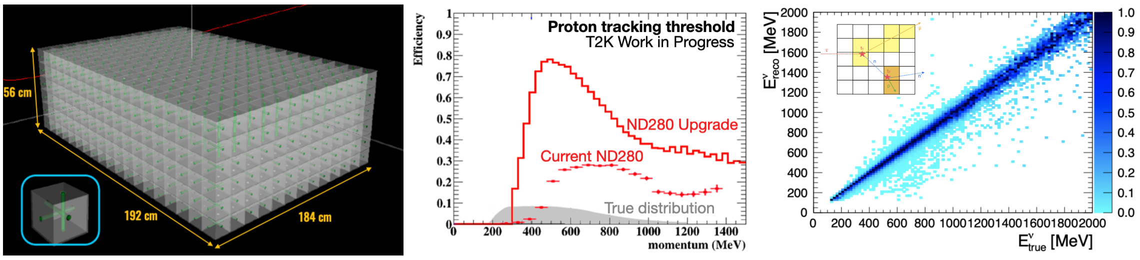

Figure 3: Right: Sketch of the Super-FGD detector. Middle: CC0π (neutrino Charged current interaction with no charged pion in the final state) selection efficiency as a function of proton momentum and not just the proton momentum with and without ND280 upgrade [20]. Left: anti-neutrino energy resolution in Super-FGD [21].

4.2 HA-TPCs

The High Angle TPC [22] features a dual-field cage design with thin walls to maximize tracking volume and Encapsulated Resistive Anode Micromegas (ERAM) detectors for high-resolution charge readout (Fig. 4). It provides nearly isotropic muon coverage, precise 3D track reconstruction, and enhanced particle identification. Utilizing charge spreading through resistive foils, ERAM improves spatial resolution, spark suppression, and electric field uniformity. Tests with cosmic rays confirmed a spatial resolution of 500 µm, dE/dx resolution under 10%, and momentum resolution better than 10% for vertical muons with momenta <1.2 GeV/c.

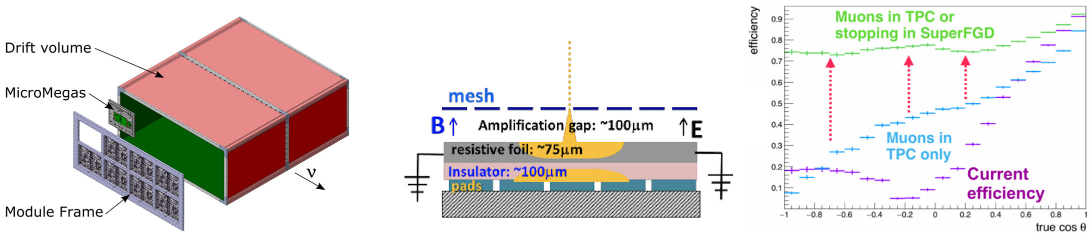

Figure 4: Right: Schematic view of the HA-TPC detector. Center: The ERAM detector. Left: Improved ND280 phase space after the ND280 upgrade.

4.3 ToF

Each ToF panel comprises 20 plastic scintillator bars, covering 5.4 m^2 per plane, with light collected by eight silicon photo-multipliers per bar [23]. ToF detectors are used to veto background particles, trigger cosmic events for the Super-FGD and High Angle TPCs, and measure charged particle crossing times. With a time resolution better than 150 ps, they can distinguish muons from electrons at 0.1–0.3 GeV and positrons from protons at 1–2 GeV, as well as resolve individual neutrino beam bunches.

5. Conclusions

T2K has entered its second phase with the successful installation of the ND280 upgrade and a neutrino beam upgrade. The beam power reached 800 kW in 2024, with plans to achieve 1.3 MW by 2027, increasing the statistics for CP violation studies. The ND280 upgrade enhances lepton and nucleon reconstruction, background discrimination, and cross-section modeling, leading to improved oscillation analyses. The detectors are performing well, with promising results already observed. The next analysis will benefit from increased statistics and upgraded near-detector samples, advancing the experiment's capabilities.

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