PROCEEDINGS OF SCIENCE

Assembly, Test and Analysis Development of the T2K Near Detector Upgrade

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The near detector of T2K is undergoing a major upgrade. A new scintillator tracker, named superFGD, with fine granularity and 3D-reconstruction capabilities has been assembled at J-PARC. The new Time Projection Chambers are under construction, based on the innovative resistive Micromegas technology and a field cage made of extremely thin composite walls. New scintillator panels with precise timing capability have been built to allow precise Time of Flight measurements. The detector is currently in assembly phase following a detailed effort of characterization during detector production. The results of multiple tests of the detectors with charged beams, neutron beam, cosmics and X-rays will be presented. Among these results, we could mention the first measurement of neutron cross-section with the superFGD and the first detailed characterization of the charge spreading in resistive Micromegas detectors.

Thanks to such innovative technologies, the upgrade of ND280 will open a new way to look at neutrino interactions thanks to a significant improvement in phase space acceptance and resolution with an enhanced purity in the exclusive channels involving low-momentum protons, pions and neutrons. Sensitivity results and prospects of physics capabilities will be also shown.

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1. Introduction

The T2K (Tokai to Kamioka) [1] is a long baseline neutrino oscillation experiment in Japan, which conducts measurements of neutrino oscillation parameters by generating a highly intense muon (anti) neutrino beam centered at 600 MeV at the J-PARC facility. This beam is measured 280 m from its point of origin by a set of near detectors (ND280), positioned prior to oscillations, with the aim of monitoring and constraining systematic uncertainties associated with the neutrino flux and interaction models. Subsequently, the far detector, situated an additional 295 km away, is Super-Kamiokande, responsible for detecting the disappearance of muon (anti) neutrinos and the appearance of electron (anti) neutrinos within the beam.

ND280, serving as the near detector in the T2K oscillation analysis, comprises two fine-grained detectors, FGD1 and FGD2, which function as the target mass for neutrino interactions. These detectors consist of plastic scintillator bars arranged in both horizontal and vertical layers, with the inclusion of supplementary water layers in FGD2. They are encompassed by three time projection chambers (TPCs), allowing precise tracking and measurement of charged particles and their momenta. All of these sub-detectors are housed within the refurbished UA1 magnet.

While the current ND280 detector provides excellent efficiency in reconstructing muons from neutrino interactions, especially in the forward beam direction, its efficiency significantly drops for high-angle and backward-traveling muons due to its design. This limited coverage of phase space, compared to Super-Kamiokande, introduces significant systematic uncertainties. ND280 also has limited capabilities in tracking short-ranged particles and backward tracks. It can only reconstruct protons with momenta exceeding 450 MeV/c. This motivates the exclusive use of muon kinematics in events with no visible mesons in the oscillation analysis. As beam exposure is anticipated to rise in the coming years, these limitations could potentially impede the precision of oscillation parameter measurements, notably the CP-violating phase δ_{CP}. Consequently, an ongoing upgrade of the ND280 detector is in progress to address these concerns. This upgrade is also accompanied by a scaling of the horn currents from 250 to 320 kA as well as an increase of the beam power from 0.5 up to 1.3 MW. The upgraded ND280 is also anticipated to serve as one of the near detectors for the Hyper-K experiment.

2. ND280 Upgrade

The ND280 upgrade, shown in Fig. 1, involves the integration of a suite of subdetectors positioned at the upstream section of the existing ND280 setup. This upgraded configuration will feature a finely segmented active target known as the Super-FGD, positioned between two high angle time projection chambers (HA-TPCs), all enclosed by a time-of-flight detector (ToF). This revamped setup is anticipated to yield substantial enhancements, including improved tracking efficiency for high-angle and backward-traveling muons, a reduced proton tracking threshold, and the potential for reconstructing neutron kinematics. The installation of these new detectors is presently in progress at J-PARC.

2.1 High-Angle Time Projection Chambers

The HA-TPC features new field cage design to minimize dead space and maximize tracking volume. It is equipped with eight Encapsulated Resistive Anode Micromegas (ERAM) on each

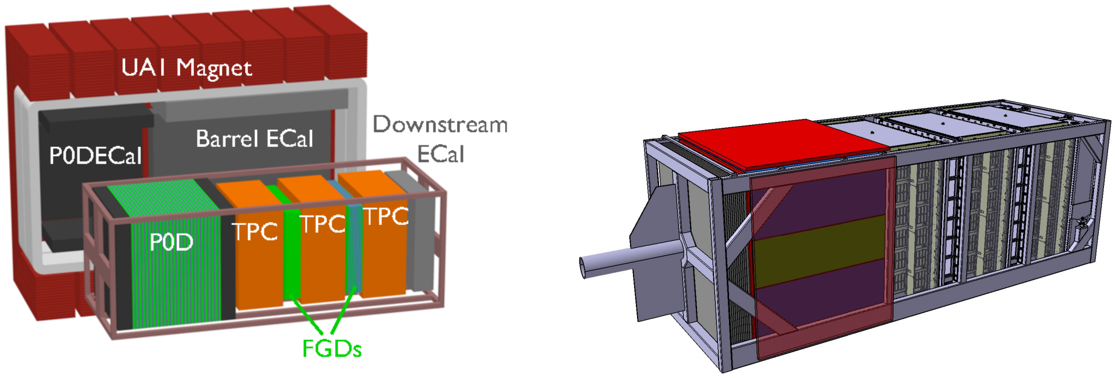

Figure 1: Sketch of the current ND280 detector (left). Sketch of the ND280 upgrade project (right), including Super-FGD (green), HA-TPCs (violet) and ToF modules (red).

of its endplates. The ERAM technology involves the deposition of a resistive layer onto the segmented anode, which serves to spread the charge across neighboring pads. This innovative approach enhances spatial resolution within a given segmentation, contributing to improved Micromegas stability and safeguarding the electronics from potential sparking incidents. The successful validation of detector prototypes for the new TPCs has been achieved through several test-beam compaigns at CERN and DESY. These tests have not only confirmed the reliability of the detector technologies but have also provided valuable insights into their performance. A spatial resolution better than 800 μm and a dE/dx resolution better than 10% are measured for all the incident angles and all the drift distances [2] as shown in Fig. 2. These results fully fulfill ND280 requirements.

A dedicated X-ray test bench is used to characterize the ERAMs, scanning each pad individually for precise measurements of gain uniformity and energy resolution, achieving an energy resolution of approximately 10%. Additionally, a comprehensive physical model, encompassing aspects like initial ionization, electron drift, diffusion effects, and readout electronics, excellently characterizes charge dispersion phenomena. This model enables simultaneous extraction of gain and charge spreading information (*RC*) from the modules. Fig. 3 shows the *RC* map and gain distribution of one ERAM. The *RC* and gain maps uniformity are studied in detail in [3].

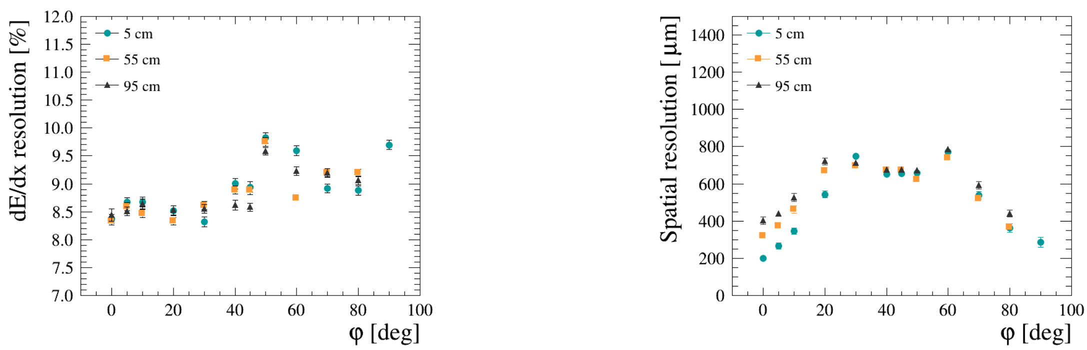

Figure 2: Distribution of dE/dx (left) and spatial (right) resolution for inclined tracks versus the angles of the inclination in the ERAM plane at different drift distances [2].

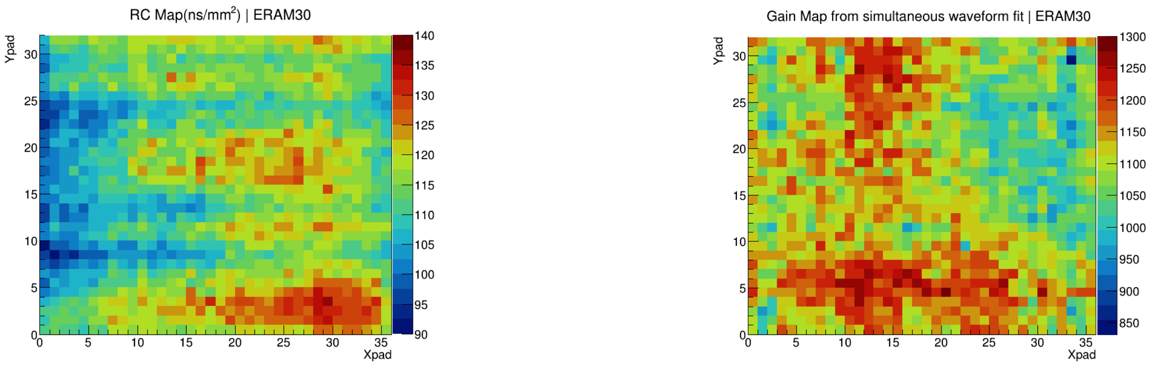

Figure 3: Distribution of *RC* (left) and gain (right) maps extracted from ERAM-30 X-ray test bench data [3].

2.2 Super-Fine Grain Detector

The Super-FGD comprises approximately two million 1 cm-sided plastic scintillator cubes, contributing to a total target mass of 2 tons. Each individual cube is coated with a reflective layer to ensure optical isolation and is intersected by three orthogonal Wavelength Shifting (WLS) fibers designed to capture the scintillation light emitted by charged particles. At one end of each fiber, there is a Hamamatsu multipixel photon counter (MPPC) for readout, while at the opposite end, an LED light source facilitates electronic calibration.

The robustness and feasibility of the Super-FGD concept have been rigorously validated through a series of beam tests conducted with scaled-down prototypes. Tests were carried out at CERN and involved an array of charged particles, including protons, muons, pions, electrons, and positrons [4, 5]. The results demonstrated its ability to resolve protons and tracks emerging from the interaction vertex as well as a good PID capabilities using the $\mathrm{d}E/\mathrm{d}x$ and range of particles [5]. The results show a channel time resolution of 1.14 ± 0.06 ns.

Another series of tests was executed at LANL, utilizing a neutron beamline to measure the total cross section of neutron interactions as a function of their kinetic energy, employing event rate depletion along the beam axis. The total neutron cross section on hydrocarbon as a function of neutron kinetic energy is shown in Fig. 4 (left) [6]. The overall data and the model agree within the uncertainties. These comprehensive tests conclusively affirmed the adherence of the Super-FGD concept to the specified requirements.

2.3 Time-of-Flight detector

To effectively discriminate between background signals originating from incoming particles, such as cosmic muons, and the outcomes of neutrino interactions within the fiducial volume, a Time-of-Flight (ToF) detector has been implemented. This ToF detector fully covers the Super-FGD and the HA-TPCs with its six planes. Each plane comprises 20 EJ-200 cast plastic scintillator bars, each measuring $12 \times 1 \times 230$ cm^3 in size. Light produced by scintillation travels through these bars and is detected at both ends by 16 Multi-Pixel Photon Counters (MPPCs).

The primary objective of the ToF detector is to achieve precise measurements of particle crossing times. The resolution obtained from a single bar is remarkably below 150 ps [7], as depicted in the left plot of Fig. 4 (right). This excellent timing precision enables the ToF detector

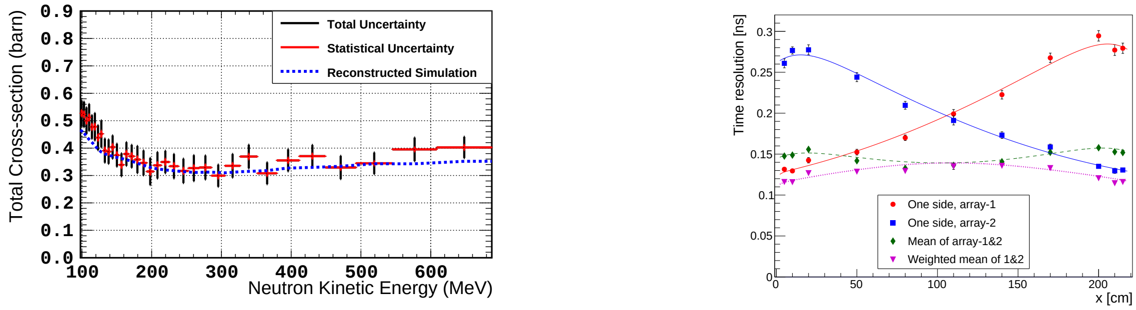

Figure 4: The total neutron-CH cross section as a function of neutron kinetic energy (left). The black vertical bars represent the total uncertainty and the red the statistical uncertainty [6]. The Geant4 `Bertini` model is shown in blue. Time resolution of one-side readout (approximated by solid curves), the resolution of two-side readout (approximated by broken curves) as a function of distance along the bar (right) [7].

not only to function as a veto mechanism for the elimination of background signals but also to serve as a trigger for cosmic muon-based calibration of the Super-FGD and HA-TPCs. Furthermore, its precise timing data holds the potential to enhance particle identification capabilities.

3. Physics Impact of the Upgrade

The upgraded ND280 detector has been demonstrated to enhance sensitivity to nuclear-model uncertainties by utilizing observables derived from both lepton and nucleon kinematics [8]. The Super-FGD's capability to reconstruct hadrons at a low threshold level (300 MeV) opens up opportunities to leverage transverse kinematic hadron variables shown in Fig. 5, such as missing transverse momentum ($\delta\vec{p}_T = |\vec{p}_T^{\,\ell} - \vec{p}_T^{\,N}|$), boosting angle $\delta\alpha_T$, and visible energy defined as $E_{\text{vis}} = E_\ell + E_N$ (where $\vec{p}_T^{\,\ell}$ ($\vec{p}_T^{\,N}$) are the lepton (hadron) outgoing transverse momentum and E_ℓ (E_N) are the kinetic energy of the outgoing lepton (hadron)).

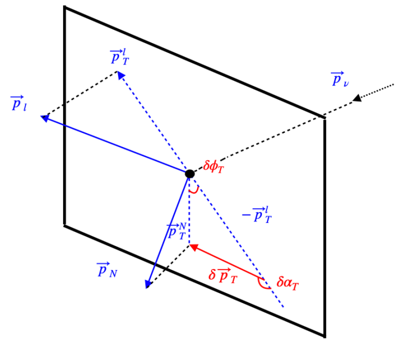

Figure 5: Schematic representation of the transverse kinematic variables.

However, the introduction of nucleon kinematics into the analysis introduces new systematic uncertainties, particularly those associated with detector systematics and nuclear-model uncertainties related to nucleon Final State Interactions (FSI) [9]. Based on extensive simulations, benchmarked against prototype test beam data and the long-term data-taking experience with ND280, it is expected that systematic uncertainties stemming from detector modeling will be well managed. It has been demonstrated in [8] that nucleon FSI can also be effectively constrained through the utilization of the boosting angle $\delta\alpha_T$. The precision of this constraint is made possible by the low tracking thresholds for protons (and neutrons) in ND280 Upgrade and the absence of degeneracy or correlation with other nuclear-model uncertainties in $\delta\alpha_T$. The use of an improved estimator of neutrino energy, based on the sum of muon energy and nucleon kinetic energy, has been investigated and shows interesting sensitivity to nuclear removal energy shifts.

4. Conclusion

The T2K experiment is embarking on a new phase marked by the imminent installation of the upgraded ND280 in 2023. The essential elements of this upgrade are nearing their final stages of integration and have exhibited good performance. The enhanced ND280 will directly address uncertainties related to neutrino interactions through the implementation of a novel suite of detectors. These detectors feature complete polar angle coverage, enhanced spatial resolution, neutron detection capabilities, and lowered tracking thresholds. Additionally, the physics program demonstrates promising prospects for successfully mitigating systematic uncertainties, ultimately facilitating more precise measurements of neutrino oscillation parameters.

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