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# The upgrade project of the T2K near detector

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The T2K neutrino oscillation experiment established the $\nu_\mu \to \nu_e$ appearance with 10% of the original beam request of $7.8\times10^{21}$ 30 GeV protons on target (POT). In view of the J-PARC program of upgrades of the beam intensity, the T2K-II proposal extends the run up to $20\times10^{21}$ POT to establish the charge-parity (CP) violation at $3\sigma$ level for a significant fraction of the possible $\delta_{CP}$ values. To achieve this goal, it is important to accomplish near detector upgrades to reduce the overall statistical and systematic uncertainties from approximately 6% to the level of 4%.

The T2K near detector ND280 upgrade project was launched in January 2017, and the proposal was submitted to the CERN SPSC and to the JPARC PAC in January 2018. ND280 Upgrade implements two horizontal high-angle time projection chambers (HA-TPCs), a highly segmented scintillator detector Super-FGD, and time-of-flight (TOF) detectors to the upstream of the current near detector. HA-TPCs are built to achieve the wide angle acceptance with the light field cages and resistive Micromegas detectors for the charge readout. SuperFGD consists of $1\times1\times1$ cm$^3$ plastic scintillator cubes readout by three WLS fibers directed to multi-pixel photon counters (MPPCs), providing detailed tracking and particle identification (PID) information. TOF complements the HA-TPCs and Super-FGD PID by determining track direction and time information. Combination of these detectors is planned to be installed to obtain a $4\pi$ acceptance for neutrino charged current interactions with improved tracking performance for low energy charged particles.

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T2K [3] has observed the $\nu_\mu \rightarrow \nu_e$ appearance with $6.6 \times 10^{20}$ POT data [4], which is approximately 10 % of the original request of $7.8 \times 10^{21}$ POT in 2021. This establishment has lead to charge-parity (CP) violation in the lepton sector by comparing $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation probabilities. The latest T2K oscillation analysis results are presented in ICHEP2018 with collected $1.49 \times 10^{21}$ and $1.12 \times 10^{21}$ POT data with neutrino and anti-neutrino focusing modes, respectively, with stable beam power at 485 kW, and it rejects CP conservation at $2\sigma$ confidence level in both mass orderings [5].

In order to to achieve $> 3\sigma$ sensitivity to CP violation, the T2K collaboration makes a proposal, T2K-II, to extend the physics run to collect $20 \times 10^{21}$ POT in 2026 [6]. Upgrade project of the beam power is planned during this run extension, and it is anticipated to increase the MR beam power from 485 kW to 1.3 MW by 2026 to improve the proton deliver rate per year. This improved statistics gives significance to achieve $> 3\sigma$ sensitivity to CP violation for approximately 40% of the $\delta_{CP}$ values with known mass ordering.

ND280 Upgrade is proposed in 2017 to reduce the systematic uncertainties from $\sim$6% to the level of 4%. We expect to achieve the $> 3\sigma$ sensitivity to CP violation at approximately $5 \times 10^{21}$ less POT with the reduced systematic uncertainties, which is approximately two years earlier than the original expectation. ND280 Upgrade is necessary to reduce the systematic uncertainties from neutrino cross section that can be constrained by the near detector measurement.

## 1. Current ND280

ND280 consists of combinations of subdetectors contained in the 0.2 T UA1 dipole magnet. The tracker consists of three time projection chambers (TPCs) [7] and two fine grained detectors (FGDs) [8] sandwiched by TPCs. FGDs consist of alternating layers of vertical and horizontal plastic scintillator bars with wavelength shifting (WLS) fibers passed through them. FGDs act as active target trackers with total mass of 2.2 tons which readout the scintillation light with multi-pixel photon counters (MPPCs). The $\pi^0$ detector (P0D) [**?**] is placed at the upstream of ND280, and the entire subdetectors are surrounded by electromagnetic calorimeters (ECALs) [**?**]. ND280 measures particles produced by neutrino interactions prior to neutrino oscillations to provide constraint on neutrino flux and cross section models.

There are two major limitations with the current ND280 designs: wide angle acceptance and low momentum measurement. While it has good acceptance for forward-going tracks, ND280 has poor acceptance for wide angle and backward tracks due to the orientation of scintillator bars and TPC coverage. In order to provide constraint on the cross section model for SK with $4\pi$ acceptance, it is important to achieve wide angle acceptance for ND280 as well. The low momentum measurement can be utilized to constrain the nuclear recoil models.

## 2. ND280 Upgrade

ND280 Upgrade project proposes to implementing new upstream tracker to improve the wide angle acceptance and low momentum measurement. The new upstream tracker consists of two High-Angle TPCs (HA-TPC), fine grained scintillator target Super-FGD, and time-of-flight (TOF) detectors. Figure 1 shows the layout of ND280 Upgrade. Super-FGD is sandwiched by two horizontal HA-TPCs, and the entire tracker region is surrounded by TOF detectors to provide timing information of particles.

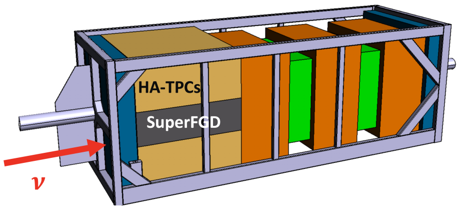


**Figure 1:** Layout of ND280 Upgrade. Referenced from [1].

HA-TPCs have performance that is similar to the TPCs that are installed in the current ND280 but with improved detector technology. In order to achieve the acceptance to the wide angle, they are designed in horizontal structure with dimensions of $1.8 \times 0.6 \times 1.8$ m$^3$ with resistive Micromegas. The field cage with multi-layer structure designs with carbon fiber and aramid fiber based layers are investigated to minimize the material budget.

TOF serve their purposes to provide timing information for track reconstruction. Combined with the track information obtained by trackers, ND280 Upgrade has improved particle identification and background rejection of interactions outside the target. The expected timing resolution is below 100 ps, and the development of a cast plastic scintillator design with arrays of $6 \times 6$ mm$^2$ silicon photomultiplier photosensors is in progress at University of Geneva.

Super-FGD [2] is the newly designed, fine-grained scintillator target for ND280 Upgrade. It consists of $1 \times 1 \times 1$ cm$^3$ plastic scintillator cubes with reflector surfaces obtained by chemical etching [9]. The full size target consists of $180 \times 60 \times 200$ scintillator cubes with active mass of 2.2 tons, and WLS fibers are passed along each side of the cubes to readout the scintillation light from three views by MPPCs to provide measurements at the neutrino interaction vertex with high granularity and $4\pi$ acceptance. Super-FGD prototype production method with injection molding process is established by INR RAS, Russia.

Using the SuperFGD protoyes, the first beam test was performed at CERN T9 area on October 2017 using $5 \times 5 \times 5$ prototype target [10]. The light yield in a cube, optical cross talk between neighboring cubes, and timing resolution are measured by CAEN digitizers. An another beam test was performed in June 2018 at CERN T9 area. This $8 \times 24 \times 48$ cm$^3$ prototype target was tested with OMEGA CITIROC electronics designed for Baby MIND spectrometer [11]. The prototype was magnetized by the MNP17 magnet platforms to apply 0.2-1 T magnetic field to obtain charge ID and momentum measurements. The data analysis of the June 2018 beam test is in progress.

Comparison of the performance between the current and upgrade ND280 configurations are done with preliminary simulation studies. In order to evaluate the wide angle acceptance, the muon neutrino charged-current (CC) interaction selection efficiencies are calculated. T2K muon neutrino flux prediction is combined with GENIE [12] neutrino interaction simulation to prepare the sample statistically equivalent to $1 \times 10^{21}$ POT exposure in neutrino enhanced mode. The neutrino interaction simulation is then processed with the GEANT4 [13] detector simulation to perform the TPC track selections. The studies show that the selection efficiencies of backward and wide-angle events increase by approximately 40% with the ND280 Upgrade configuration.

Scintillator detector performance is evaluated by comparing the preliminary track reconstruction efficiencies between Super-FGD and FGD-like targets. SuperFGD has a uniform efficiency higher than 90% while the FGD-like target has low efficiency for particles travelling parallel to the bar orientation. The lower proton momentum threshold is improved from 500 MeV/c with FGD-like target to 300 MeV/c with SuperFGD.

## 3. Conclusions

T2K-II is the proposal to extend the T2K physics run to achieve $> 3\sigma$ sensitivity to CP violation. ND280 Upgrade is the project to implement new upstream trackers to obtain wide angle acceptance and low momentum measurement by near detectors to reduce systematic uncertainties in the oscillation analysis. The ND280 Upgrade project is launched in 2017, and the proposal has been submitted to the CERN SPSC [1] and to the JPARC PAC in January 2018. Research and development of various components of the ND280 Upgrade detectors are in progress.

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