NP07: ND280 Upgrade project

The T2K ND280 Upgrade Working Group

Abstract

The upgrade of the T2K Near Detector, ND280, has been approved by the SPSC in April 2019 and it is one of the Neutrino Platform projects (NP07). In this document, prepared for the SPSC Annual review, we summarize the main milestones obtained in the last year of the project, towards the installation of the detectors at J-PARC in 2021.

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1 T2K and the ND280 upgrade project

The T2K experiment is a long-baseline neutrino oscillation experiment, currently ongoing in Japan. T2K has been the first experiment to detect the appearance of electron neutrinos in a muon neutrino beam and is now searching for CP violation in the leptonic sector by precisely measuring appearance probabilities of neutrino and antineutrinos. Such measurement requires both, larger statistics and a better understanding of systematic uncertainties. In order to improve the latter, an upgrade of the T2K Near Detector, ND280, is being conducted and is expected to significantly reduce the impact of systematic uncertainties on T2K oscillation analyses and, more in general, to improve the current knowledge of neutrino cross-section models.

The ND280 upgrade, shown in Fig. 1, will consist in replacing one of the sub-detectors, the P0D, the most upstream inner detector of ND280, with two horizontal TPCs (HA-TPC) and a horizontal fully active carbon target in the middle (Super-FGD). Six Time-of-Flight (ToF) planes will be installed around the HA-TPCs and the Super-FGD.

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

These detectors are being constructed and will be assembled, mostly at CERN, in 2020 and 2021 before being shipped to Japan in the second half of 2021. The main improvements that will be obtained thanks to the upgrade with respect to the current Near Detector configuration (see Fig. 2) are:

- higher efficiency in reconstructing muons produced in neutrino interactions and emitted at high polar angle with respect to the neutrino direction, thanks to the two high angle TPCs.
- higher efficiency in detecting low momentum protons and pions produced in neutrino interactions thanks to the high granularity and the 3D reconstruction capabilities of the Super-FGD.

In 2019 we submitted to the SPSC a TDR describing the ND280 upgrade [1]. Such document has been reviewed by the SPSC and, following their positive recommendations, the ND280 upgrade became, in April 2019, one of the approved projects in the Neutrino Platform (NP07). In this document we summarize the main milestones obtained in the last year of the project.

2 The Super-FGD

The Super-FGD is a novel design of fine grained fully active plastic scintillator detector and it consists of ~2 millions of optically independent cubes of plastic scintillator, read out along three orthogonal directions by wavelength shifting (WLS) fibers, coupled at one end with a Multi-Pixel Photon Counter (MPPC). The active part consists of $192 \times 184 \times 56$ cubes, with the size of each cube of $1 \times 1 \times 1$ cm$^3$. The total weight of the Super-FGD will be ~2 tons.
2.1 Cubes production and Layers assembly at INR

The scintillator cubes are produced at UNIPLAST Co. (Vladimir, Russia) at a stable rate of \(\sim 100\)k cubes per month. The size uniformity of the cubes is excellent, with \(\sigma \sim 30\) \(\mu m\). Slightly larger variations, of the order of \(\sigma \sim 50\) \(\mu m\) are observed when the holes are drilled. The cubes are then delivered to INR (Moscow) where a quality check is performed, checking that stainless steel needles can be inserted in all the three directions. This quality check rejects \(\sim 5 - 7\)% of the cubes. In total more than one million of cubes have been already delivered to INR and, at this rate, it is expected that the production of cubes will be completed by the end of 2020.

The cubes passing the quality check are assembled in xy layers with fishing lines. The full chain from the quality check to the assembly of the xy layer is shown in Fig. 3. By the end of January, 20 full-size layers (192×184 cubes) had been assembled. In addition, in order to test the sagging of the Super-FGD, 56 narrow-size layers (192×15 cubes) have been assembled together into a tower as shown in Fig. 4. Such tower corresponds to the full height of the Super-FGD and the cubes used to assemble it are equivalent to 4.5 full-size layers.
2.2 Choice of the assembly method

Two different methods have been investigated for the assembly of the cubes into the final Super-FGD detector. The first is the fishing-line method, in which fishing-lines with 1.3 mm diameters are inserted into the cube holes (1.5 mm diameter). First we form strings of 192 cubes and then 184 strings are connected, again with fishing lines, to form a xy plane of the required dimension. In a second step, the xy layers will be merged into the final 3D detector.

The alternative method uses ultrasonic welding to assemble cubes between two thin sheets with controlled gaps. One sheet consists into an array of $32 \times 24$ cubes and an xz layer is formed by 14 sheets. This method has the advantage of providing a rigid structure with fixed cube position but needs better quality control of the single cubes and brings additional dead materials.

An external review committee has been formed by the T2K Executive Committee to review the feasibility of the two assembly methods and the fishing line method was recommended as the baseline option:

*The baseline fishing line method has been well prototyped and is currently being implemented with a significant proportion of layers already assembled with fibre optic cables. This gives confidence that resources that are currently being utilized should be sufficient to complete the full assembly on schedule. The main outstanding question for this method relates to the seismic stability.*

*The backup ultrasonic welding method offers greater structural integrity (which could be enhanced further) and should be less labour intensive than the fishing line method. However this method requires more infrastructure development particularly for the QA. In addition the WLS fibre installation takes place at the end of the installation so any severe hole misalignment (due to a failure of the QA) would be difficult to recover from.*

Following this recommendation we decided to concentrate all the efforts on the fishing-line method and the developments of the ultrasonic welding method have been halted.
2.3 Mechanical box and sagging tests

The Super-FGD cubes will be installed inside a mechanical box, consisting of six panels. Each panel will host an AIREX foam within two thin Carbon Fiber (CF) layers. Each panel has 3 mm diameter holes spaced in a pitch of about 1 cm to allow passing the WLS fibers outside the CF box. The WLS fibers are then attached to the plastic layer with optical connectors pressurized by soft foam to ensure the contact between the fiber ends and the MPPC channels. MPPC channels are soldered on PCB with \(8 \times 8\) MPPCs array and the PCB is screwed on the box.

![Design of the Super-FGD box and connection to the MPPCs.](image)

According to FEA analysis, we expect that the weight of the Super-FGD will induce a sagging of 3–4 mm in the center of the detector. The simulation model has been validated with a prototype of the bottom layer of the box of 15 (w) x 192 (l) cm\(^2\). During the tests carried out at INR, the tower shown in Fig. 4 have been mounted on the box prototype and the sagging has been measured for different number of layers. The measurements confirmed the results of the FEA simulations, including the fact that, once the holes are drilled on the box, the sagging increases by \(\sim 20\%\). The results of these tests are shown in Fig. 6.

![Drilling of holes in the Super-FGD box prototype (left). 15×192 holes with 3.0 mm diameter and with a step of 10.3 mm have been drilled. The measured sagging as a function of the position with and without holes are shown on the right plot.](image)
2.4 Wavelength Shifting fibers, MPPCs and calibration system

In order to instrument the Super-FGD we will need 73 km of fibers (including the spare) and \(\sim 63\) k MPPCs that will be mounted on PCBs. Each PCB will host 64 MPPCs. For the fibers, the procurement is being organized and, before launching the mass production, we are finalizing the decision for the treatment of the end surface of the fibers with measurements from test benches.

Concerning the MPPCs, 50 k of them have been already delivered by Hamamatsu in Japan and the remaining 13 k will be delivered in the US. First measurements of MPPCs operation voltage with a prototype PCB have been performed, as shown in Fig. 7. Small differences in the operation voltages between the MPPCs mounted on the PCB and the ones measured by Hamamatsu before delivery have been observed and are being investigated.

![Figure 7: Design of the MPPC PCB and measured difference in the operation voltage between the MPPCs mounted on the PCB and the one measured by Hamamatsu.](image)

A Test Bench, that will allow to characterize eight PCBs simultaneously in term of gain and dark noise rate using an LED system and a Light Guide Plate (LGP) is being designed. Thanks to this system, the full characterization of the MPPCs is expected to be completed by March 2021.

A calibration system is also being designed for the Super-FGD, with an LED emitting light that is collected by the WLS fibers on the side not connected to the MPPCs. Such system has the purpose of providing regular calibration of MPPCs gain during the long-term operations. The main option foresees the LEDs mounted on a PCB on the bottom of the Super-FGD, to minimize interference with the fixation system to the basket. The light will then be distributed to the fibers through an LGP as shown in Fig. 8. Tests on prototype have shown that a light uniformity over all the WLS fibers from the same LGP within a factor of 2 can be obtained with this system. We expect to complete the design of the LED calibration system by April 2020.

2.5 Super-FGD electronics

The electronics engineers from LLR, University of Geneva and US groups (University of Pennsylvania and University of Pittsburgh) are working on finalizing the design of the Super-FGD electronics. The CITIROC chip has been chosen for the SiPM readout. Such a chip has the advantage of being well established, also used in commercial products. The Front End Boards are being designed, based on the one designed by the team at the University of Geneva for the Baby-MIND detector, which is presently being used as a part of the WAGASCI setup taking data in the ND280 pit. In order to cope with the very small space available and to reduce power dissipation, the new design requires extending the Baby-MIND one from 3 to 8 CITIROC chips, which corresponds to 96 to 256 channels.

The front end electronics will therefore be composed of 221 Front-End Boards (FEBs), each of them embedding 8 CITIROC chips, 2 ADCs and one (Intel)Arria-10 FPGA. A block diagram of these
new Front End Boards can be seen on Fig. 9. All required chips have been acquired from Weeroc (France) and will be delivered in the coming months. The FEBs will be installed in 16 crates mounted in the basket (8 on each side of the Super-FGD). The analog signals from the MPPC boards will be conveyed to the FEBs using SAMTEC flat ribbons containing 80 micro-coaxial cables each, as can be seen on Fig. 10-Left. These cables will be connected on the “front” of the FEBs (corresponding to the outermost side of the crates), by means of a small dedicated board, in order to ensure an easy and safe connection with no need to fold the cables. Each crate (see Fig. 10-Right) will host an Optical Concentrator Card (OCC) that will control 14 FEBs and send their data to the DAQ by means of optical fibers. In each crate, the OCC communication with the FEBs will be ensured by a dedicated backplane located on the innermost side of the crate.

Figure 9: Simplified block diagram of a Front-End Board. The Arria-10 FPGA will ensure the control of 8 CITIROC chips, and the digitization of the analog signals through 2 ADCs. It will also ensure all communications with the OCC through the back-plane connection.

2.6 Performance Studies with Prototypes

Two Super-FGD prototypes have already been constructed and instrumented. The first Super-FGD prototype, assembled at CERN, has 9216 cubes which are read out by 1728 MPPCs. As electronics the one developed for the Baby MIND project was used. It has same CITIROC chips adopted for the Super-FGD electronics. The second prototype, assembled in the US, has 2048 cubes and 576 channels and is read by MPPCs. Its design already takes into account several of the design concepts considered
for the final Super-FGD. For example the MPPCs are mounted on PCB in group of 64, as in the final Super-FGD design. It also uses the Baby MIND electronics for the readout.

2.6.1 CERN TESTBEAM STUDIES

The first prototype was exposed in summer 2018 during two campaigns to a particle beam at the T9 station at CERN. A dedicated trigger system was set up by the collaboration allowing to select different particle types. This was used to study the detector response to these particles with and without magnetic field. Some results are shown in Fig.11. A publication about the results is supposed to be submitted before May.

Figure 11: The light yield from 1205 cubes read out by the vertical fibers (left) and the light attenuation in the fiber measured with the testbeam prototype.

2.6.2 NEUTRON BEAM TESTS AT LANL

The detector response to neutrons is of special interest to measure anti-neutrino interactions ($\nu + p \rightarrow l^+ + n$) in the detector. Two Super-FGD prototypes have been exposed, in December 2019, to a neutron beam at the Los Alamos National Laboratory to study the detector response to this type of particle. The beam
emits neutrons with energy up to 800 MeV produced by protons impinging on a tungsten target. The beam is pulsed, allowing for the selection of the neutrons based on Time Of Flight.

Data have been taken in two locations, at 90 m and at 20 m from the target and will allow to characterize the response of the Super-FGD to neutrons. The analysis of the data is on-going and the possibility of another test beam campaign in Fall 2020 is being considered.

2.7 Next steps

The next critical milestone for the Super-FGD project is the finalization of the design and the production of the assembly box, that should be delivered to CERN by September 2020 in order to timely start the assembly of the xy cube layers that will be shipped from INR in the coming months.

The assembly at CERN will be done with fishing line and, once completed, we will ship the Super-FGD to J-PARC where the fishing line will be replaced with WLS and the MPPC PCB will be installed.

3 The High Angle TPCs

The HA-TPC will share many features with the existing ND280 TPCs, that has so far obtained completely satisfying performances. The two main innovations with respect to the existing TPCs will be the use of Resistive MicroMegas modules, called ERAM (Encapsulated Resistive Anode MicroMegas) and the use of a single layer of solid insulator laminated on a composite material for the field cage, while for the current ND280 TPCs, two gas-tight boxes, one inside the other were used.

The ERAM modules, naturally introduces a spread in the charge on the anode plane, allowing for a lower density of readout pads and eliminating the risks of discharges (sparks). This allows to remove the protecting diodes on the front end cards. The new design of the field cage, instead, minimize the dead space and maximize the tracking volume.

![Figure 12: Parameters and sketch of the new HA-TPC.](image)

3.1 ERAM modules and DESY test beam

So far we have tested two MicroMegas modules. The first one (MM#0), based on the layout of the existing TPC MicroMegas but with the addition of a resistive foil has been test in the HARP field cage during a Test Beam campaign at CERN in 2018 and the results have been published in [2]. The performances in terms of deposited energy resolution and spatial resolution are shown in Fig. 13.

The second module (MM#1), with the layout conceived for the HA-TPC (1152 pads, with dimensions of 10.1 × 11.2 mm) has been tested in a Test Beam at DESY in 2019. It should be noted that thanks to the superior performances of the resistive technique, a reduction in the total number of channels of 33% is obtained.
Figure 13: Deposited energy resolution (left) and spatial resolution (right) for the MM#0 module tested at CERN in 2018.

The tests at DESY have been done in a short chamber (15 cm drift distance) with electrons of 4 GeV/c and with and without magnetic field. The test beam allowed to characterize and validate the design of the new detector and to make precise measurement of the resistivity of the module as a function of the pad position.

Figure 14: Schematic cross-section of a resistive MicroMegas module and photo of the first ERAM module produced.

The results of these test beams allowed to launch the production of the pre-series of the ERAM modules (see Fig. 14). These modules will have the same design of MM#1 except for the fact that the thickness of the glue will be increased from 75 to 200 µm, in order to decrease RC and increase the spread of the charge.

The first ERAM module to be used in the HA-TPC have been delivered at Saclay in February 2020 and it will be followed by 7 additional modules for which the DLC foils have been received by B-Sputter.
3.2 First TPC Field Cage prototype

The TPC field cage is designed as a single box structure, with the walls made of insulator. The box also makes up the field cage and two drift volumes are defined by a central common cathode. On the other side the volumes are closed by an anode supporting the 8 ERAM modules mounted on a module frame.

In 2019 we produced and tested one small scale prototype that has the same drift length of the final TPC (1 m) but smaller transverse dimension (43×43 cm), suitable for the installation of one ERAM module. The prototype, shown in Fig. 15, has been manufactured by NEXUS (Barcelona) and tested in Air at Legnaro before being moved to CERN.

![First TPC prototype](image)

Some issues were observed concerning the mechanical rigidity, the electrical aspects and the gas tightness and are reported below. Following these findings, the design of the TPC field cage has been slightly changed as it will be reported in 3.4.

**Mechanical aspects**

During the measurements done at Legnaro ∼ 20 bubbles were observed, due to air trapped along the kapton valley between strips. These bubbles can be cured by doing a tiny hole, sucking the air with a syringe and sealing the hole with Kapton tape.

In Legnaro we also measured the flatness of the prototype field cage shapes, with maximal deviations of 200 µm for the inner surface, 300 µm for the flange plane. The transverse cross section shape is constant with deviation from a square shape of 800 µm. Such values are well within the requirements that were given for the HA-TPC.

**Electrical aspects**

Some interruptions of electrical continuity have been found in the first prototype in the field strips. These were spotted while checking the resistance of the strip between the two strip ends and were cured for the prototype by using small samples of strip foils to bridge the interruption.

Such interruptions were not found in the mirror strip, although one short circuit between 2 not adjacent mirror strip was found, precisely located and cured. The risks of such short will be mitigated in the future by adding a kapton layer between the strip foils and the Twaron layer.
Gas Tightness

One of the main issues with the prototype was its gas tightness, with gas leaks at the level of 30 l/h. During the visual inspection we spotted some sources of leaks due to the difficulties in gluing the POM-C that was used for this first prototype.

This particularly affects the flanges and, after the results of the prototype, we decided to use G10 instead of POM-C. G10 is much easier to glue and, in order to test the gas tightness, we produced a small prototype of field cage using G10 for the flanges at ORVIM, Venice, in which the gas leak was below 1 l/h.

3.3 Prototype cosmics tests at CERN

After these tests the TPC prototype was moved to CERN where the T2K gas mixture was fluxed inside the Field Cage and High Voltage tests were performed. At the begin some sparks had been observed in the region close to the cathode and were solved by properly shaping the external grounded shielding. After this fix it was possible to operate the TPC at an HV of 18 kV for several days. Tests at higher voltages were also performed, and stable operations were possible at the design value of 25 kV.

The analyses of these cosmics data is on-going and some preliminary results are shown in Fig. 16.

![Figure 16: Measurements with the TPC prototype at CERN: Cluster multiplicity (top left), arrival time (top right), charge per cluster (bottom left) and charge truncated mean (bottom right).](image)

3.4 Final TPC field cage design

Taking into account the results from the first TPC prototype, it has been decided to review the design of the field cage in order to improve the fabrication process and reduce the risk of leaks. In particular we will use G10 instead of thermoplastic (far easier to glue and stiffer) and we will produce a single-piece G10 flange, in order to reduce the needs for screws. The procedure for the strip-layer placing system at NEXUS have been improved, based on the results of the first prototype and a new insulating Kapton layer between the strips and the Twaron layers will be added to reduce the risks of shorts.

Also the design of the mold has been improved in order to avoid blisters on the strip faces and to reduce the possibility of damages during the dismounting of the mold. All these changes have been agreed with NEXUS and will be tested in a second prototype, of the same size of the first one, that will be delivered by NEXUS in the first half of 2020.
An external review of the TPC field cage has been organized by the T2K Executive Committee in order to validate the design of the TPC and it is expected to give its recommendations by the middle of 2020.

3.5 Gas system

Within the ND280 upgrade project, it is planned to build a new gas system that will serve both, the new TPCs and the existing ones. We will keep the same gas mixture, Ar-CF$_4$-iC$_4$H$_{10}$ (95:3:2) with a flow rate that will allow 1 volume change per 6 hours and with a fresh injection of gas of 10% in the circulation flow.

The new gas system modules will be designed based on CERN standard and profiting of the CERN experience with gas system from the LHC experiments. The gas system will be running on a Programmable Logic Controller and it will be controlled/monitored using the standard WinCC-OA SCADA interface.

3.6 TPC electronics

The TPC electronics will be based on the use of the AFTER chips, that had been designed for the existing ND280 TPCs. The AFTER chip is a 72-channel device that includes preamplifiers and shapers with programmable gain and shaping time coupled to a 511-time bucket switched capacitor array (SCA).

8 AFTER chips will be mounted on the Front-End Cards (FEC), that will be installed parallel to the ERAM modules. Each ERAM module will be read by two FECs for a total of 64 FECs for the two HA-TPC. The two FECs on each ERAM will be connected to a Front-End Mezzanine (FEM) card that performs the control, synchronization and data aggregation of the two FECs of a detector module.

As Back-end electronics we will use the TDCM, a generic clock, trigger distributor and data aggregator module designed for several projects, including the upgrade of T2K.

![Figure 17: The first FEC (left) and FEM (right) prototypes.](image)

In the last six months we have produced the first prototypes of the FECs and of the FEMs (see Fig. 17). These prototypes have been already tested together. The communication between the two cards was established and it was possible to acquire the pedestals from each channel. The pedestals have the expected values and the next step will be to test the new cards on the TPC prototype at CERN.

3.7 Next steps

One of the critical steps for the HA-TPC project is the beginning of the production by CERN/EP-DT-EF PCB manufacturing facility of the ERAM detector. We expect to produce 3 ERAM detectors per month, thus needing $\sim 15$ months for the production and qualification of the required 32 ERAM modules.
The first ERAM modules and the electronics will be installed at CERN on the first half of the TPC field cage that will be delivered by NEXUS in Summer 2020 where cosmics tests will be done.

In addition, another test beam campaign has been scheduled at DESY in October 2020 and will allow to test, with electron beam and magnetic field, a final ERAM module on the TPC field cage prototype.

4 The Time Of Flight detector

The ToF system will be used to veto particle originated outside of the Super-FGD target. It will also improve particle identification and will provide a cosmic trigger for calibration of detectors which are enclosed inside. Each ToF module is composed by an array of 20 plastic scintillator bars which are stacked in a plane. The total area of one module is $2262 \times 2495$ mm$^2$ (size of aluminum frame). The size of each bar is $2200 \times 120 \times 10$ mm$^3$. The material is a plastic scintillator EJ-200. The bars are wrapped in aluminium foils and a black polyethylene stretch film on top to ensure opacity.

The current status is that all the scintillator bars, the MPPCs, the amplifiers boards, etc. have been procured and the bars have been wrapped and are ready to be assembled into the 6 ToF planes. A photo of one ToF module on the assembly table is shown in Fig. 18 (top-left). After the assembly is completed, we will start the tests with cosmics for the commissioning of the electronics and the calibration.

It is foreseen that for these tests the ToF planes will be installed on a baby-basket that is a replica of the ND280 basket and has been already delivered CERN. The setup will also be used to test with cosmics the HA-TPC and the Super-FGD when they will be ready.

The experimental setup for the cosmic ray measurements is shown in Fig. 18 (top-right). The trigger was formed by the coincidence of signals from two scintillator counters installed on top and bottom with respect to the bar under test. The mean value of the times registered by both beam counters was considered as a reference and was subtracted from measurements of the main bar.

The dependence of the measured time versus position of the crossing point along the bar as viewed by both MPPC arrays is shown in Fig. 18 (bottom-left). The graphs are approximated by linear functions whose slopes represent the effective average speed of light along the bar, which is found to be $v_{eff} = 15.9$ cm/ns. One can convert this value into the effective average reflection angle using the refraction index of the plastic, which gives $\theta_{eff} = 33.1^\circ$.

The time resolution of the counter as registered by the arrays is shown in Fig. 18 (bottom-right). The individual resolution evolves from 130 ps for the crossing point near the sensor to 280 ps for the light propagation along the 2 m distance. This deterioration in accuracy is due to the absorption of photons and smearing of the signal leading edge during its propagation. An improvement of the resolution is observed in case of the crossing point being at the proximity of the far end. This could possibly be an effect of light reflected backwards. The resolution of the mean time and the weighted mean measurements is also shown. In both cases the time resolution is approximately 140 ps for the full length of the bar. However the weighted mean approach provides a visible advantage for interactions taking place in vicinity of the sensors.

4.1 Next steps

Only a single ToF module has been assembled so far. The mechanical assembly of other five modules will take 1 - 1.5 months. It will be followed by two weeks of tests for the light collection system when amplifiers of every single module will be powered simultaneously and respond to cosmic muons will be reordered. In the meantime, signal cables and patch panels for each module will be produced. Work on the DAQ and slow control systems will begin afterwards.
Figure 18: **Top-left:** one ToF module on the assembly table in EHN1. **Top-right:** photo of experimental setup for the cosmic ray measurements. **Bottom-left:** time detected by MPPC arrays at two ends of bar as a function of the trigger position along the bar. **Bottom-right:** time resolution obtained with two MPPC arrays, the resolution of their mean and weighted mean as a function of the trigger position along the bar.

5 **Software, Reconstruction and physics studies**

A lot of progresses were made for the reconstruction in the HA-TPC and in the Super-FGD and the integration of these detectors in the ND280 software.

We do not go into the details in this document but the ND280 Upgrade geometry is now fully implemented in the ND280 software structure and the structure for the detector response is also implemented.

Different algorithms are being developed using test beam data the reconstruction of tracks in the Super-FGD and in the HA-TPC. For the HA-TPC we will use the existing T-REX reconstruction while for the Super-FGD we are developing new reconstruction algorithms. Such work is in development phase and the goal is to have a first complete version of the reconstruction algorithms by the end of 2020.

Concerning the ND280 upgrade expected physics output, we have recently submitted a paper [3] proposing a new method to reconstruct the neutrino energy in $\nu_\mu$ interactions, based on the measurement of the kinematics of the neutron emitted in $\nu_\mu$ CCQE interactions. Such measurement will be possible in the ND280 upgrade thanks to the superior performances of the Super-FGD.

In addition, we have contributed to the Hyper-Kamiokande Near Detector CDR, performing sensitivity studies.
Figure 19: Precision on the ND280 upgrade constrain on the binding energy (left) and on the contribution from multinucleon interactions (2p2h) as a function of the POT. In the right plot two options are tested for the uncorrelated bin-by-bin uncertainty: 1% (black line) and 10% at $8 \times 10^{20}$ scaled proportionally to the POTs (dashed blue line). The constraint is obtained by performing a fit in $\delta p_T$ versus $\delta \alpha_T$ for events with one reconstructed muon and one reconstructed proton.

Such document is not yet public, but, we have demonstrated that, thanks to the improved reconstruction of muons and protons and by using single transverse variables, such as $\delta \alpha_T$ and $\delta p_T$, we will reduce the uncertainty on the binding energy, that is the dominant systematic uncertainty in today’s T2K oscillation analyses [4], from $\sim 6$ MeV to $\sim 1$ MeV while the uncertainty on the multinucleon interactions (2p2h) normalization will be reduced to 2% (see Fig. 19).

6 Project Time Schedule

Due to the current exceptional situation, the time schedule has a large uncertainty. We expect not only a shift but consider the possibility that materials needed for some tasks will have a delay in delivery after the normalization of the situation. Since the impact can still not be evaluated, we present here the milestones we had worked out before the current crisis:

- **04/2020**: Finishing assembly of 6 TOF panels at CERN
- **07/2020**: Delivery of first half of full TPC to CERN
- **09/2020**: Testing of first half TPC with electronics at CERN
- **10/2020**: Delivery of SFGD mechanical box to CERN
- **12/2020**: Finishing commissioning of TOF panels at CERN
- **02/2021**: Delivery of 2nd TPC modules to CERN
- **03/2021**: Finishing SFGD assembly with fishing lines at CERN
- **04/2021**: Shipment of SFGD, 1st TPC and TOF panels to J-PARC
- **04/2021**: Finishing production of ERAM modules at CERN
- **06/2021**: Shipment of 2nd TPC to J-PARC
- **09/2021**: Delivery of first SFGD electronics to J-PARC
- **09/2021**: Installation of 1st TPC in basket
- **11/2021**: Installation of SFGD in basket
- **01/2022**: Installation of 2nd TPC in basket
03/2022: Finishing of installation at J-PARC

For the work of the detector assembly done at CERN, We have submitted a document to the Neutrino Platform in order to request the spaces and services that will be needed.

References


