The DAQ system development for the T2K new near detector Super-FGD

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T2K experiment

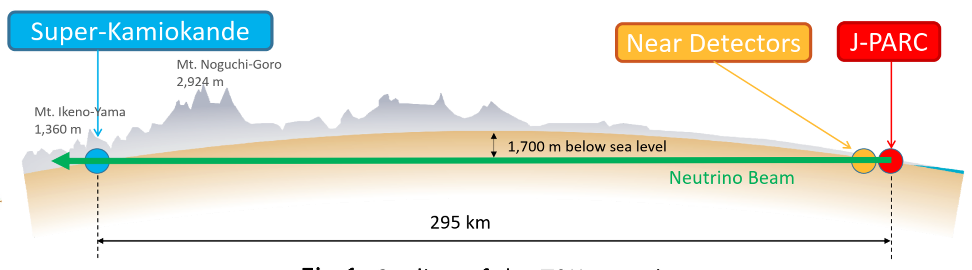

Fig 1. Outline of the T2K experiment

Long-baseline neutrino oscillation experiment in Japan, which mainly aims for precise measurement of neutrino oscillation parameters by detecting $\nu_\mu(\bar{\nu}_\mu)$, $\nu_e(\bar{\nu}_e)$ from J-PARC.

Recent result [1] constrained CP violation phase δ_{CP} in the lepton sector to

$$\delta_{CP} = -1.97^{+0.97}_{-0.62}\ \left(-1.44^{+0.56}_{-0.59}\right)$$

($\delta_{CP} = 0, \pi$, that is, CP conservation is excluded at the 90% confidence level)

ND280 upgrade

CP violation: calculated from $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ oscillation probabilities
±30% effect in T2K (see Fig.2)

statistics:

~100 $\nu_e(\bar{\nu}_e)$ events in the far detector Super-K until now [1].
The following upgrades will yield ~20 times larger statistics.

- Far detector upgrade: Super-K→Hyper-K (2027). 8.4 times larger fiducial volume
- Beam power upgrade: 760kW (Dec. 2023) → 800kW (Jun. 2024) → 1.3 MW (2028)
- Horn current upgrade: 250 kW → 320 kW

systematics:

~5% mainly from the neutrino-nucleus interaction uncertainty (see Tab.1)
ND280 upgrade for finer particle tracking etc. to achieve 4% systematics

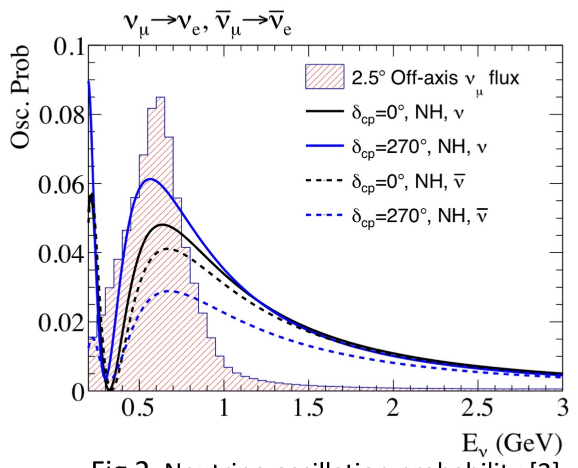

Fig 2. Neutrino oscillation probability [2]

Tab 1. Uncertainties on the number of observed neutrino events in Super-K. The events are divided into 1Rμ (ν_μ-like), 1Re (ν_e-like). "FD+SI+PN" means the combined uncertainties from Super-K (FD), secondary particle interactions (SI), and photo-nuclear (PN) effect. The uncertainties on neutrino flux and interaction are constrained by ND280, but they are still dominant in the total uncertainty. [1]

Sample		Uncertainty source (%)			Flux⊗Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

- ND280

Near detector placed at 280 m downstream of the T2K carbon target.
Detect neutrinos and constrain neutrino interaction models, cross sections etc.
To reduce systematics, replace the upstream part of ND280 with Super-FGD, High-angle TPC (HAT), ToF.

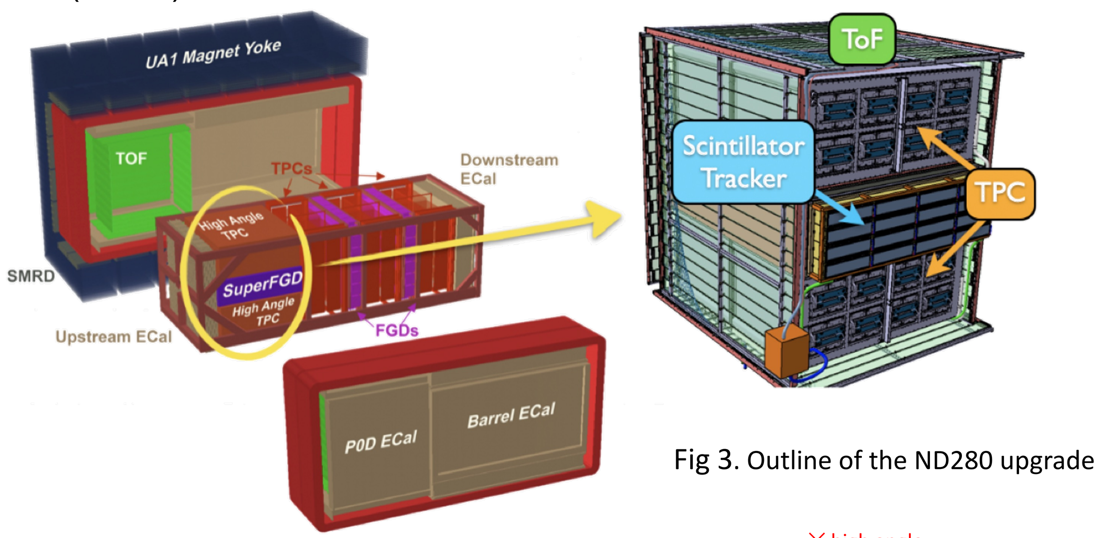

Fig 3. Outline of the ND280 upgrade

- Super-FGD
  - Active target & scintillation tracker
  - 1cm³ plastic scintillation cubes
  - 2 million cubes (192 x 182 x 56)
  - 3D readout with WLS fibers
  - 881 MPPC-PCB x 64ch = 56k ch MPPC

→ detect high-angle/low p events
→ improve cross section systematics w/ better understanding of nuclear model

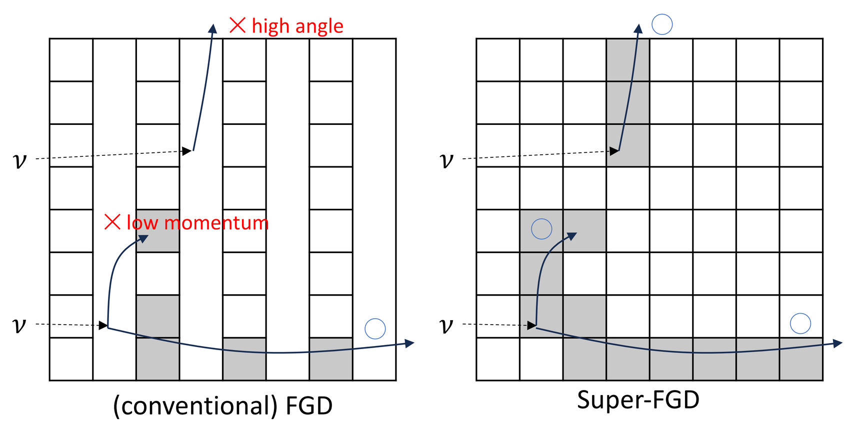

Fig 4. Conventional detector vs Super-FGD

Super-FGD DAQ system

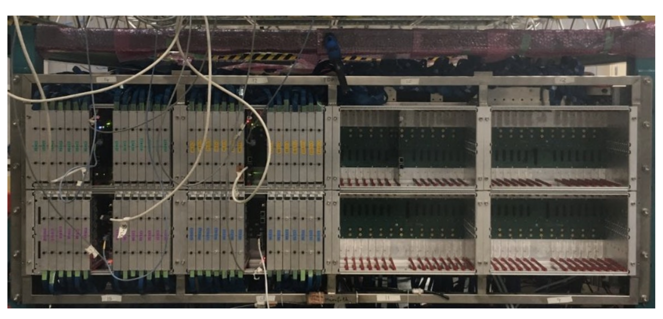
Fig 5. Electronics installed at the side of Super-FGD

Super-FGD DAQ system consists of:

- FEB (frontend board) w/ cold plate
  - each FEB has 32ch ASIC × 8 and connected to 4 MPPC-PCB
- OCB (optical concentrator board) x 16
  - each OCB is connected to 14 FEBs via Backplane
  - Aggregate data from FEBs, coordinating timing/event info from MCB
  - FPGA and CPU are on the same board and MIDAS frontend program (see the bottom diagram) is sit on the CPU
- MCB (master clock board)
  - Distribute clock and trigger for upgraded ND280

Hit times, digitized MPPC amplitudes are sent to DAQ system
(~2000 Kbps, w/ LED triggers ~8000 Kbps)

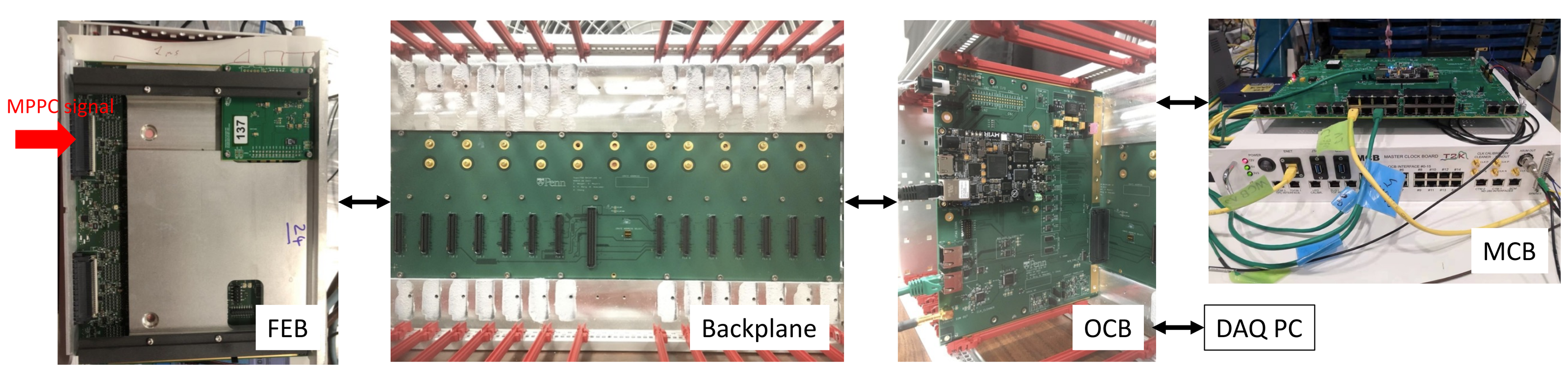

Fig 6. Electronics pipeline for Super-FGD

Super-FGD integrates into the MIDAS DAQ system used by the ND280.
*MIDAS: A general-purpose system for event-based data acquisition in small and medium scale Physics experiments.
Send data from each sub-detector to the remote PCs using RPC.
The software structure is shown in Fig. 7.

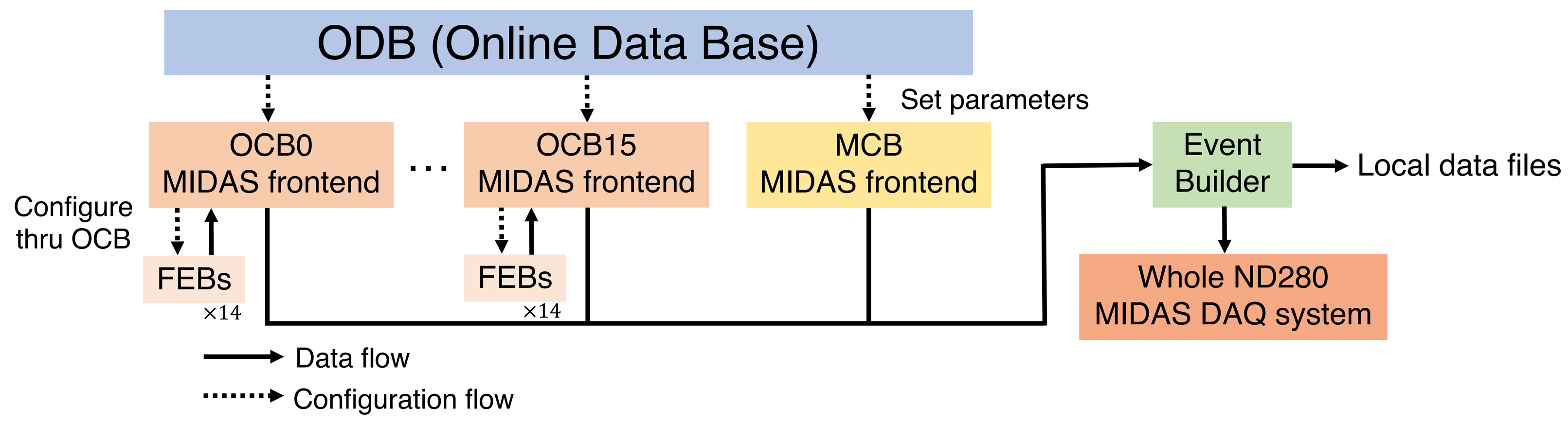

Fig 7. Outline of the Super-FGD DAQ system using MIDAS

The following table shows a feature list of the DAQ system:

Feature	Note
Faster data transfer	Direct memory access (DMA) to read out data from FPGA
Register access control	DAQ and SlowControl frontends run as separate processes. POSIX semaphores are used to prevent simultaneous access to the same FPGA registers
Electronics configuration	All DAQ-related electronics configuration can be performed through MIDAS backend program. - FEB level: configuration files containing separate settings for each of the ~60,000 readout channels can be generated and loaded at once. - MCB/OCB level: trigger modes etc. can be set from the backend
Realtime error checking	Check and report errors from pushing data through electronics and event number mismatch during event building
Histogramming data	Make histogram while taking LED data to reduce data rate Done within OCB MIDAS frontend

The DAQ system offers several types of triggers for various studies:

Trigger	Description
Beam	Synchronized with the J-PARC beamline Neutrino events are taken with this trigger
Cosmic	Triggered by signals in the conventional ND280 sub-detectors (FGD/TripT) This provides large light yield and useful to study detector response, alignment etc. (Super-FGD itself can also provide cosmic trigger. If sum of 16 OCB data are in the range of predetermined values, trigger will be issued)
LED	Triggered by LED attached on some part of the surfaces of Super-FGD This provides low light yield data which are useful to measure gain and baseline
Pedestal	Take data if signal exceeds predetermined threshold. Usable to measure dark noise rate etc.

Results

We could successfully run Super-FGD together with HAT, ToF and the conventional ND280 sub-detectors and took cosmic/beam data in late December 2023 [3], even though some parts of the upgraded detectors were missing at that time. Fig.8 (a) shows a picture of the upgraded detectors taken from the side and (b) shows the neutrino interaction candidate event. In June 2024, we could finally take beam data with all upgraded/conventional detectors which will be used for physics analyses.

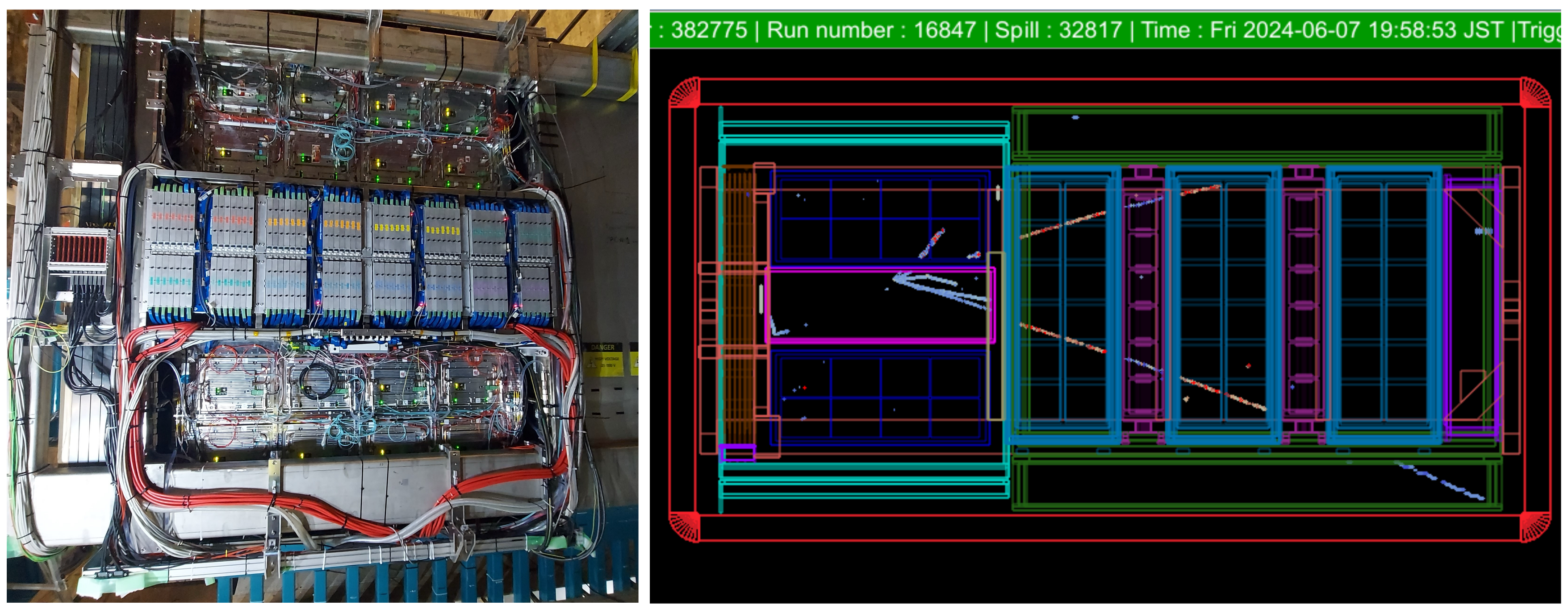

Fig 8. (a) Picture of Super-FGD, HAT and ToF (left). (b) One of the neutrino interaction candidate events found in the beam data taken in June 2024.

Summary

Super-FGD is a new component of the ND280 which plays role as a tracker as well as a target. It has 4π acceptance and provides us cross section of neutrino interactions having outgoing particles at high angle. It started taking cosmic/beam data in Dec. 2023. It successfully took beam data, and some neutrino interaction candidate events were found. The data taken in June 2024 will be used for physics analyses and it will improve the sensitivity to the CP violation in the lepton sector.

References

[1] T2K Collaboration, K. Abe *et al.*, "Measurement of neutrino oscillation parameters from the T2K experiment using 3.6 × 10²¹ protons on target", *Eur. Phys J. C* **83** 9, (2023) 072011.

[2] L. Kormos, "Recent T2K Neutrino Oscillation Results", *PoS* EPS-HEP2019 (2020) 394.

[3] ICRR Latest News, "【Press Release】T2K experiment enters a new phase with significantly improved sensitivity for its world leading neutrino oscillation research—Started data taking with upgraded accelerator neutrino beam and new detectors—", https://www.icrr.u-tokyo.ac.jp/en/news/14651/