3D сегментированный детектор СуперFGD для исследований нейтринных осцилляций в эксперименте T2K

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ИЯИ РАН

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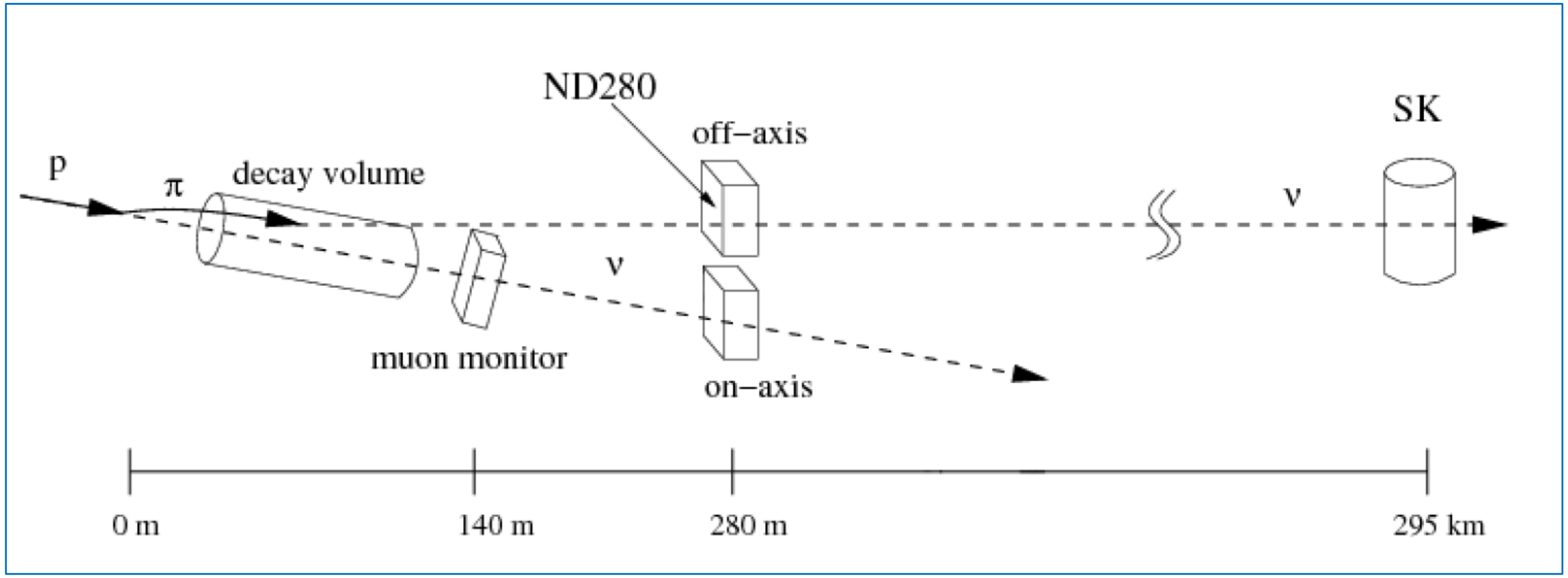
The T2K Experiment

The T2K (Tokai–to–Kamioka) experiment is a long-baseline neutrino experiment in Japan studying neutrino oscillations. The main goals of T2K are:

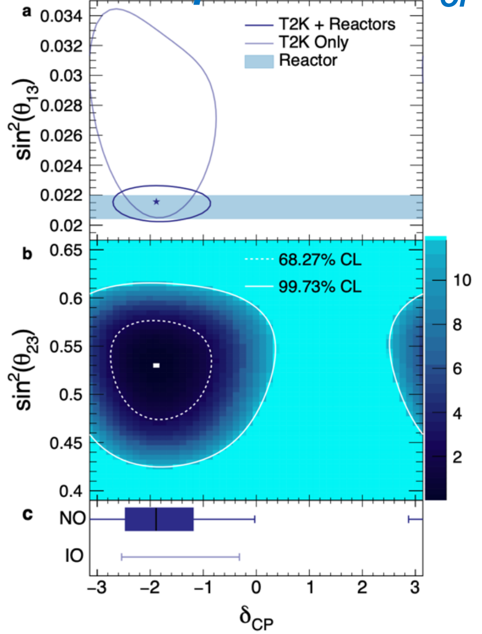
- *Study of electron neutrino appearance in the muon neutrino beam (Measure θ_{13}).*
- *Precise measurement of oscillation parameters (Δm^2_{23} and θ_{23}) via disappearance studies.*
- *Study of CP violation providing further constrain on the δCP phase.*
- *Measurements of various neutrino interaction cross-sections for different types targets.*

The experiment uses a muon-neutrino beam generated at the J-PARC accelerator in Tokai and sent 295 km to the far detector, Super-Kamiokande, in Kamioka. The focus of this talk will be on the near detector ND280 and its upgrade project.

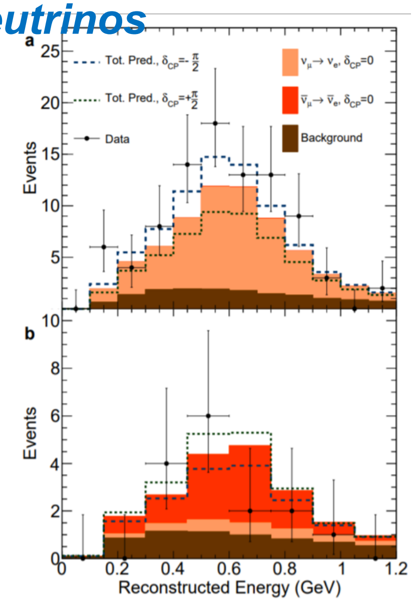


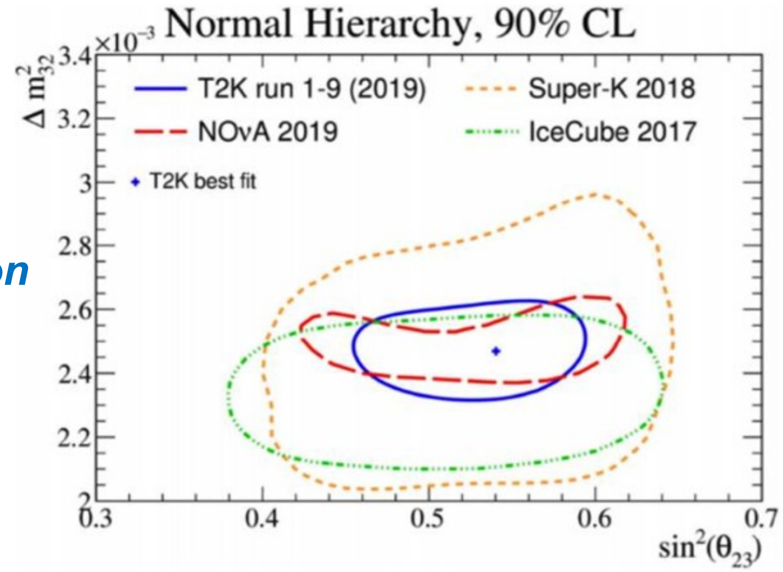
The T2K Results

Constraints on CP violating
parameter δ_{CP}

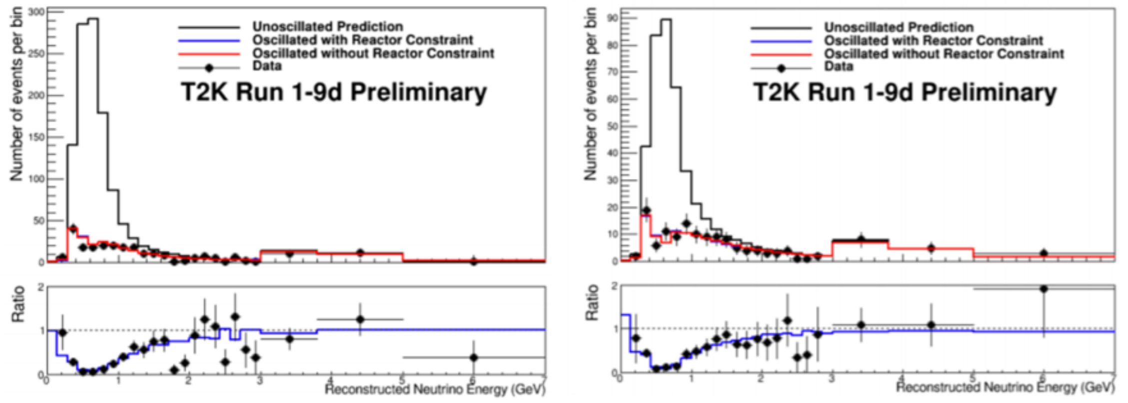


Number of observed electron neutrinos in the beam of the muon neutrinos

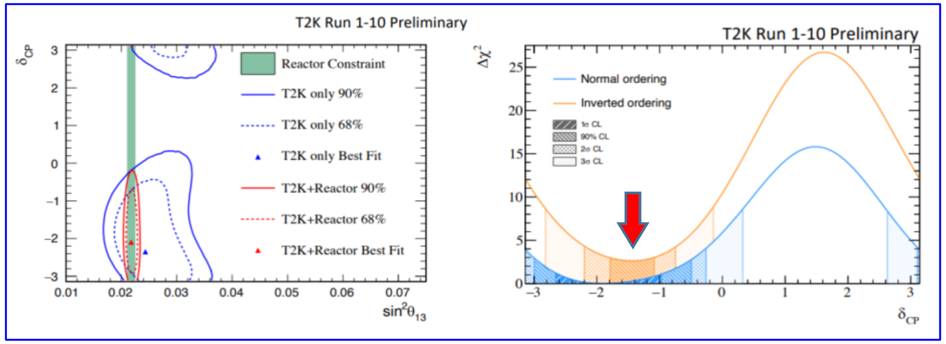




The $\sin^2(\theta_{23})$ and Δm^2_{32} restrictions under the normal hierarchy of neutrino masses

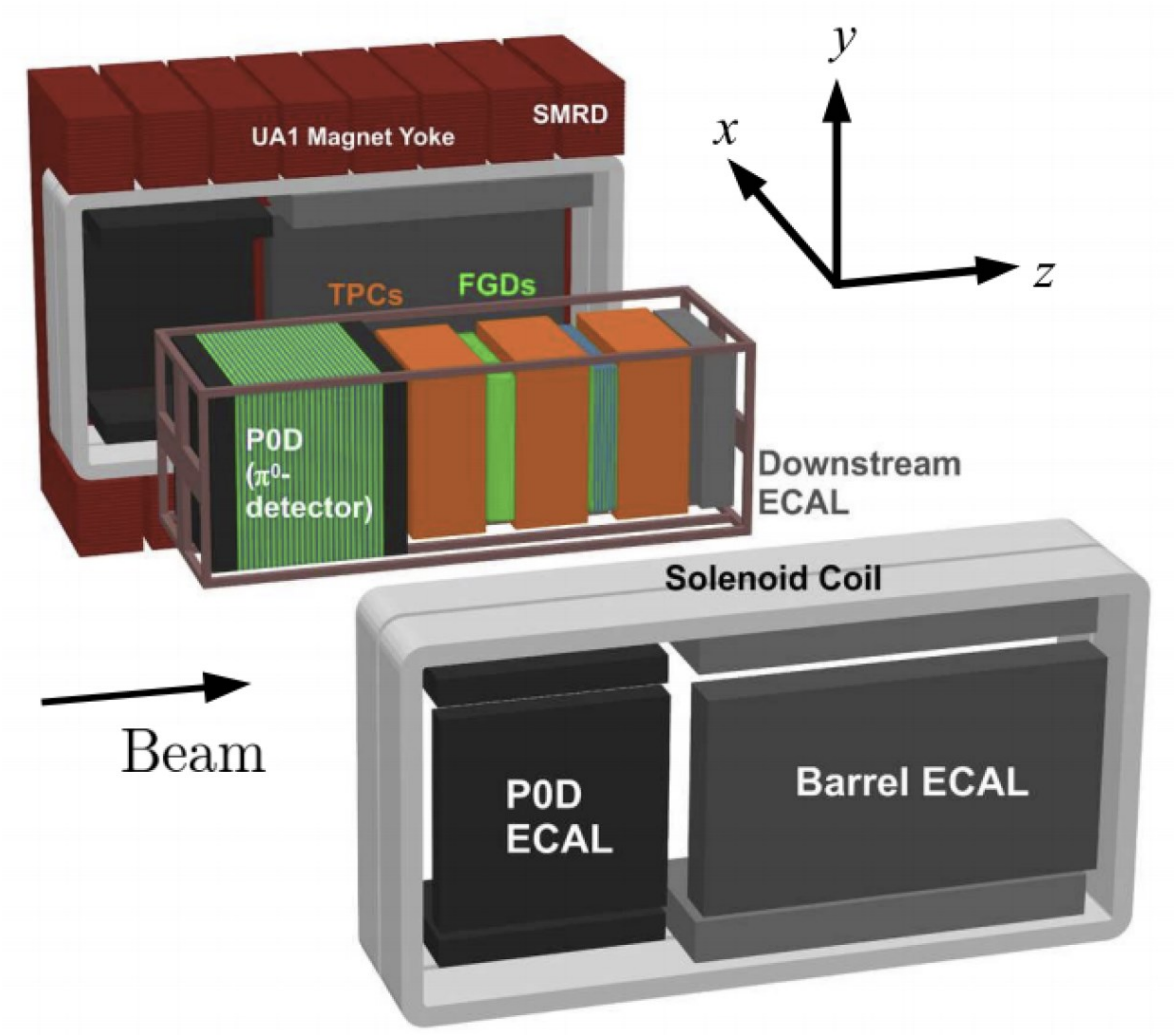


Number of observed muon neutrinos and antineutrinos in the far detector with/without oscillations



Indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\pi/2$

The ND280



- *The near detector, placed at a distance of 280m (off-axis) from the target.*
- *Measures the flux, flavor content and energy spectrum of the neutrino beam, and helps study neutrino-nucleus interactions.*
- *Although it provides excellent efficiency in the forward region, the efficiency suffers significantly for scattering angles larger than 40 degrees.*
- *It has limited capabilities in identifying backward tracks and racking short-ranged particles.*
- *To address these limitations, an upgrade project for the ND280 was launched in February 2017 and is planned to run in 2022.*

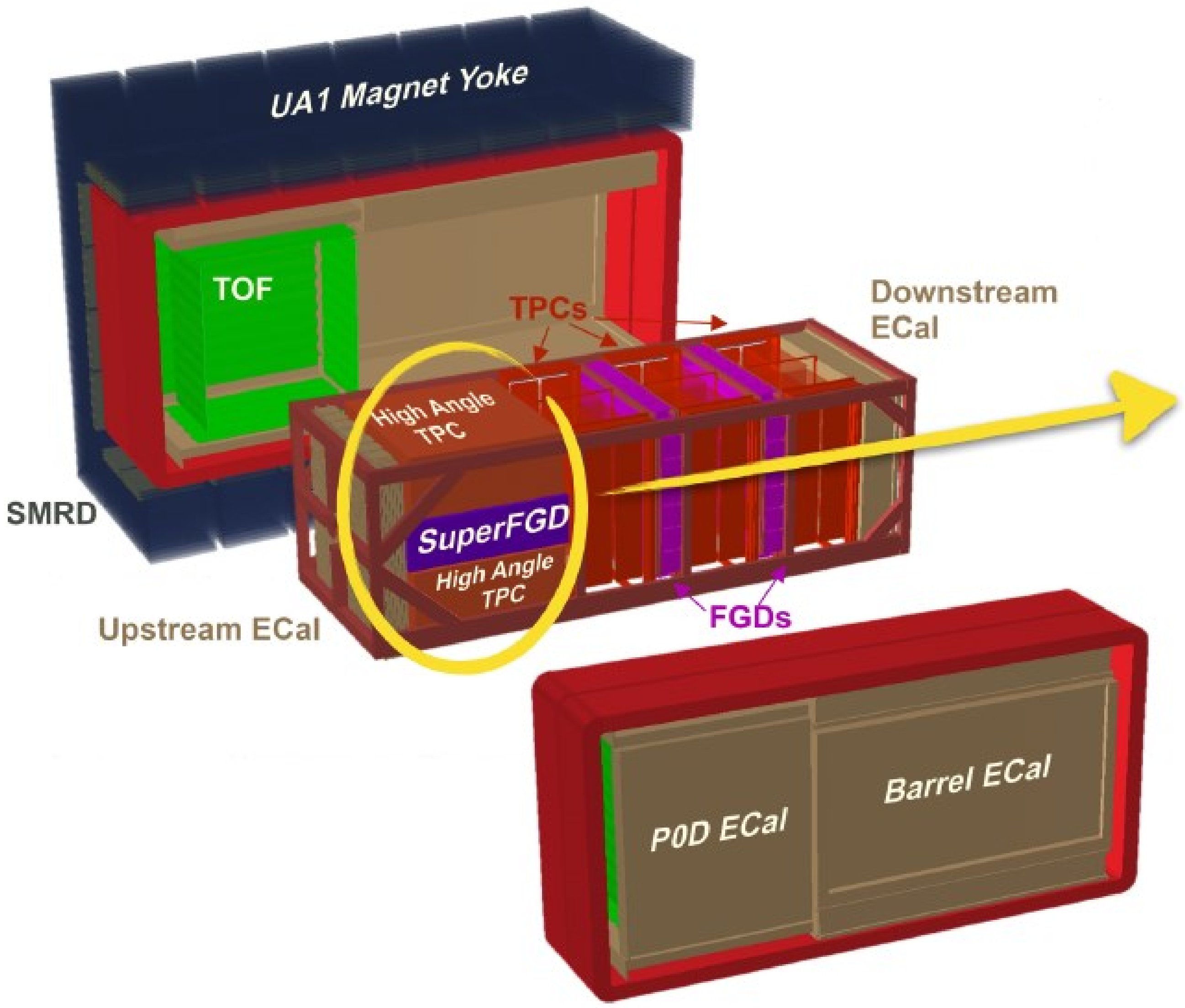
Motivation of ND280 Upgrade

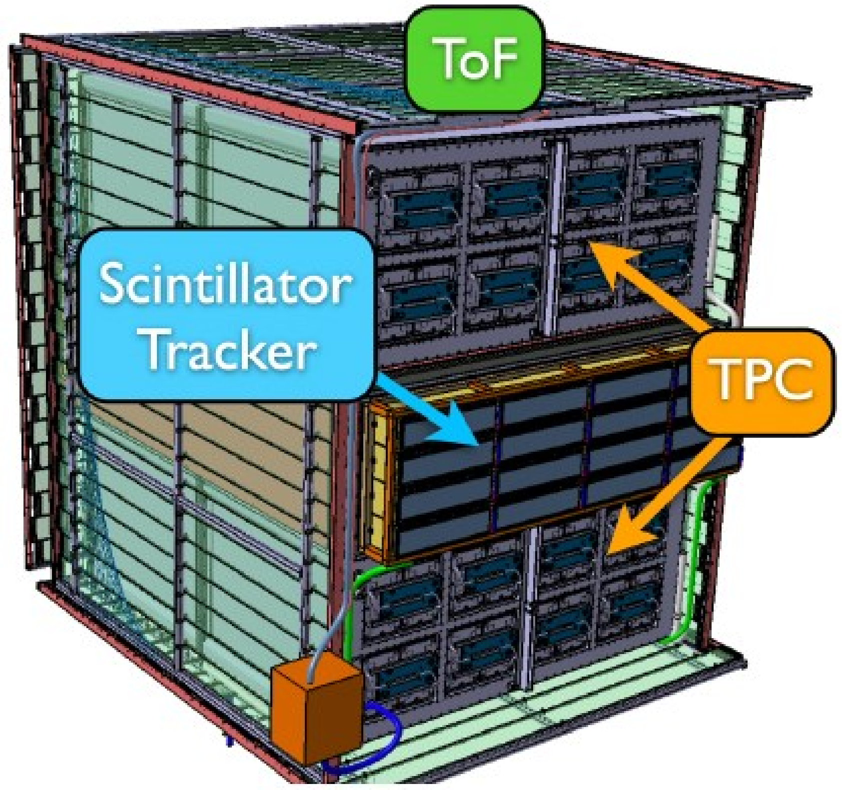
- *Uncertainties of current T2K oscillation measurements are dominated by statistics*
- *However, systematics will limit T2K (and HyperK) sensitivity in future*

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

On average the error on the systematic parameters can be reduced by about 30% in the ND280 upgrade configuration

- *Important to measure neutrino interactions in all phase space*
- *Precisely detect particles produced at any angle*
- *Reduce detection threshold, measure protons with low threshold*
- *Measure neutrons in anti-ν_μ interactions*
- *Reduce background, obtain better track identification using TOF*
- *Provide electron/gamma separation*
- *Reduce total systematics to ≤ 4% level (from current ~ 6%) for appearance modes*

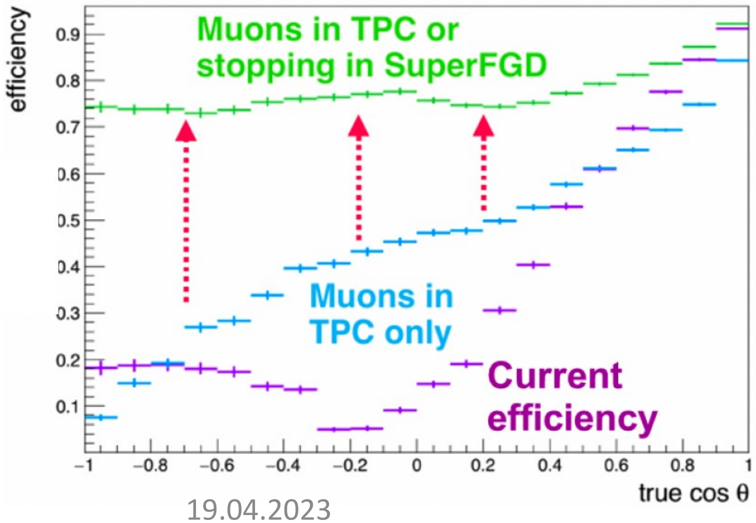


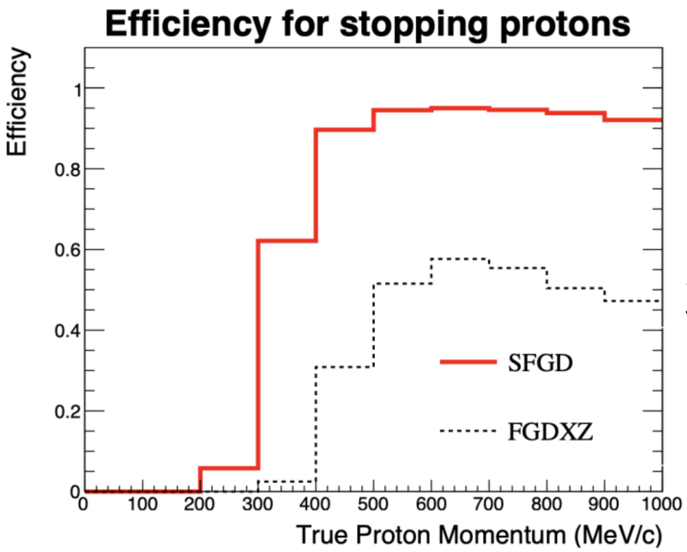


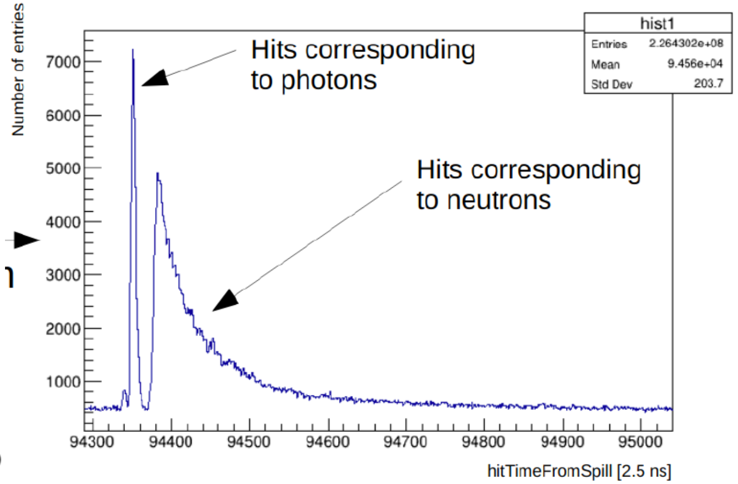
The Upgraded ND280

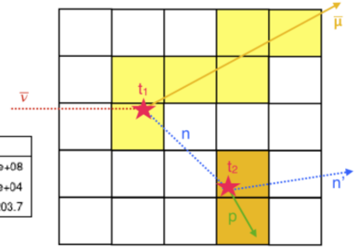
Advantage of the Upgrade

- The performance of the new ND280 was compared to that of the current design using a selection of ν_μ Charged-Current interactions applied to simulations. The new design clearly shows an improved acceptance for high angle and backward tracks.
- The SuperFGD will be able to offer a high precision probe of the nuclear effects responsible for some of the dominant systematics in neutrino oscillation analyses → reduced systematics.
- This fine granularity of the SuperFGD allows for the detection of short proton tracks around the CCQE vertex, which is very important for the T2K analysis.
- SuperFGD provides reconstruction of the neutrino energy by measuring the muon and proton energies (Current ND280 uses only muons for reconstruction of the neutrino energy)

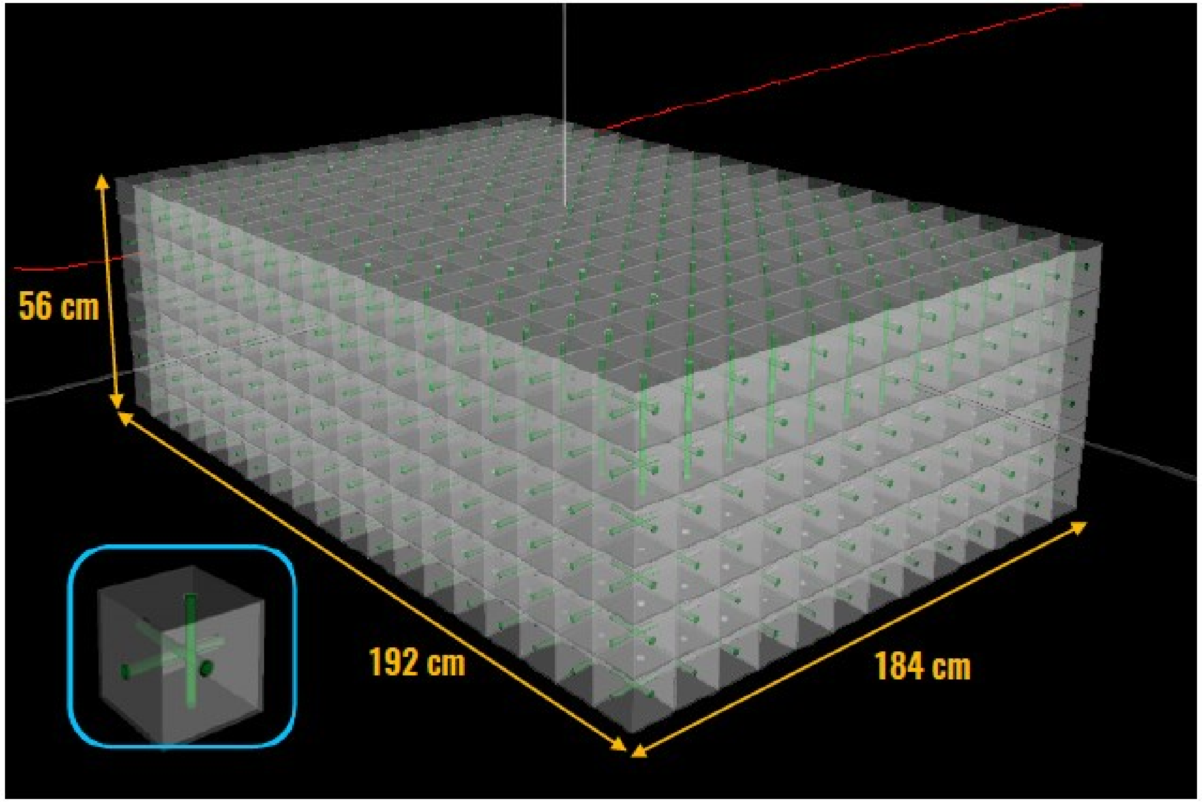






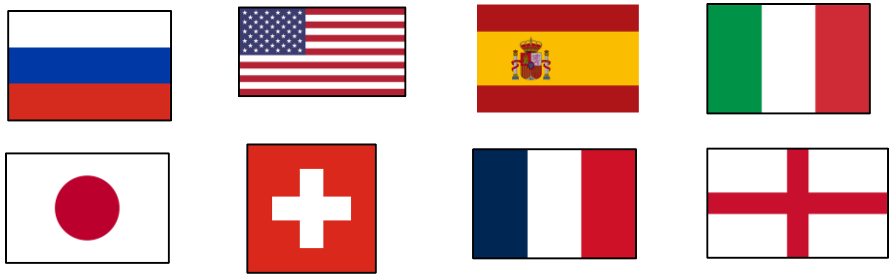


The Super FGD

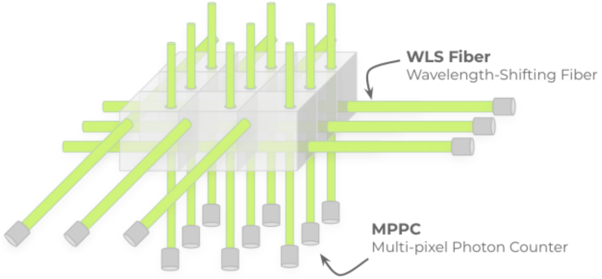


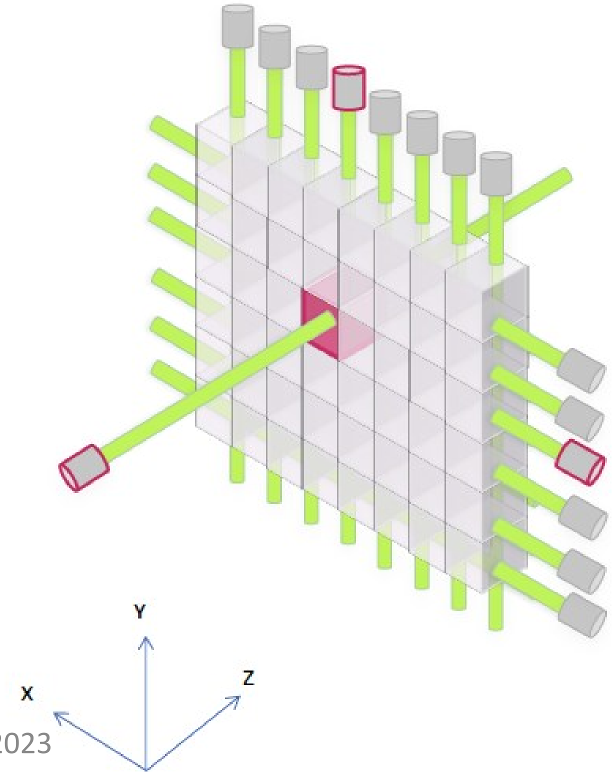
The SuperFine-Grained Detector is the active target for neutrino interactions in the upgraded ND280 detector. It is a plastic scintillator detector composed of a large number of optically independent 1x1x1 cm3 cubes read out along three orthogonal directions by wavelength shifting fibers.

The Super FGD collaboration



Cubes

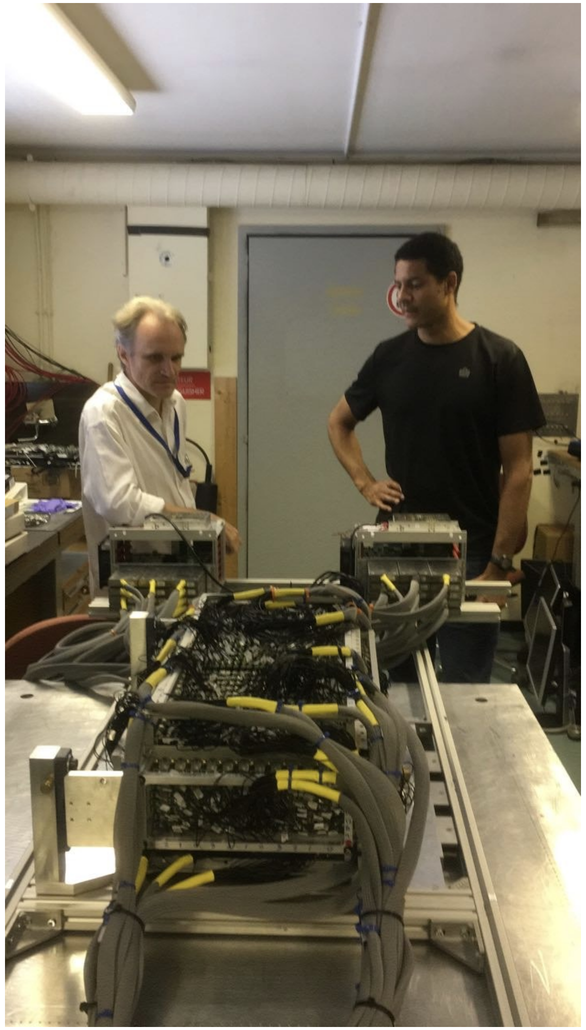




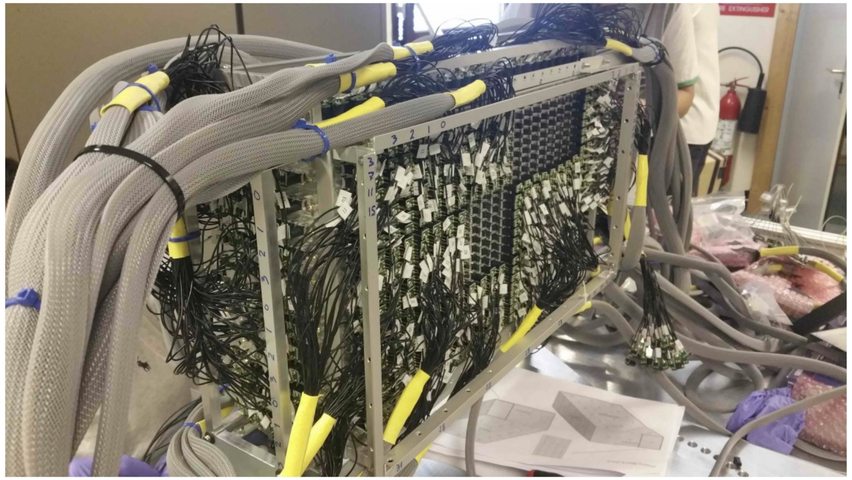
- *Cubes produced by injection molding*
- *The building blocks of the SuperFGD are the scintillating cubes. The 1 cm cubes are made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.*
- *To make the cubes optically independent, they are coated with a chemical reflector by etching their surface with a chemical agent.*
- *Produced by Uniplast in Vladimir, Russia.*
- *The SuperFGD (192x56x184 cm3) is about 2 million cubes.*

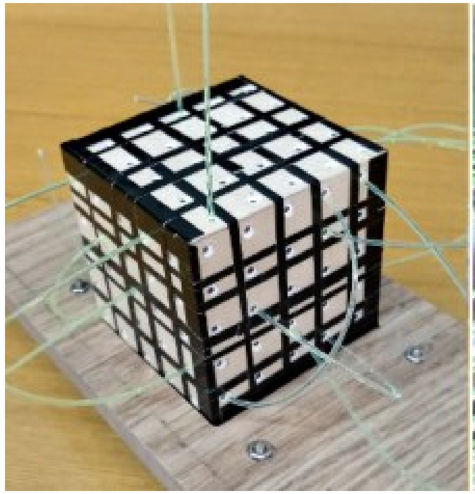
- *The SuperFGD provides 3D readout for each cube.*
- *Each MPPC can give information on 2 of the three coordinates of the cube. This information, along with the amplitude and time of the signal, can be used to create projected 2D event displays.*
- *Sets of 3 2D hits can be matched in order to locate the cubes where the interaction occurred.*

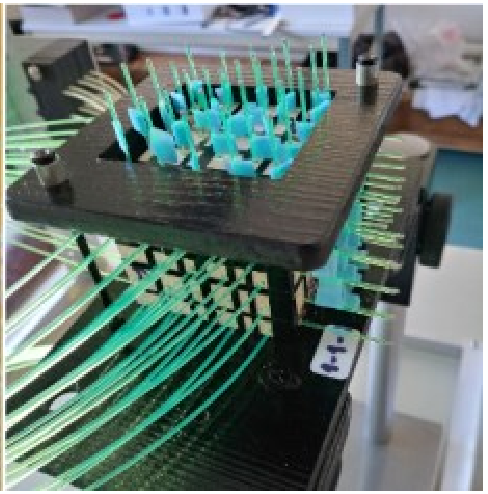
SuperFGD Prototypes tests



- We tested two SuperFGD prototypes at CERN with charged particles. A small 5x5x5 cm3 prototype in 2017, and a larger (24x8x48 cm3) in 2018.
- During the CERN beam test, both muon and hadron beams were used with momentum ranges between 0.5 – 4 GeV/c.
- The prototype construction helped improve the detector assembly procedure, and the beam tests provided preliminary insights on the capabilities and performance of the detector.

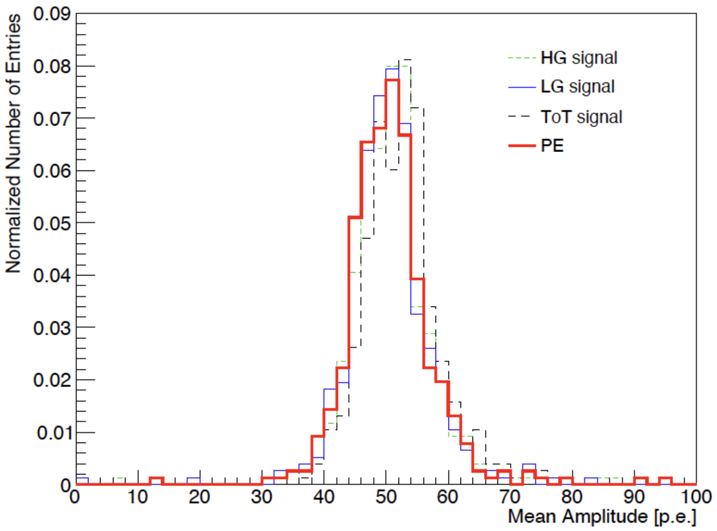




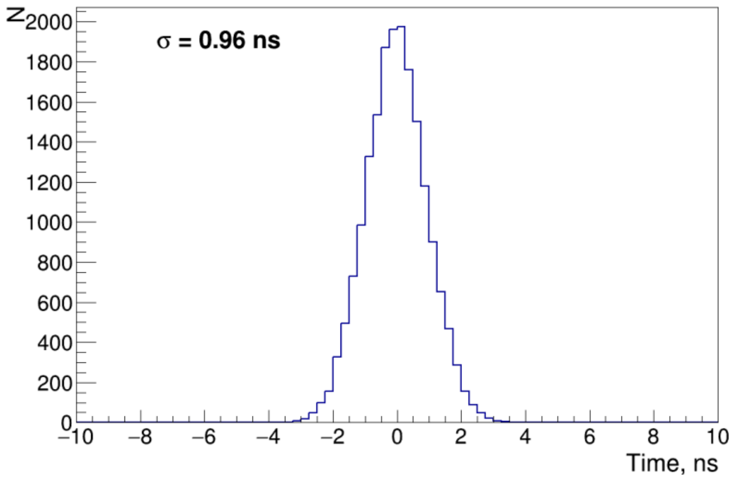


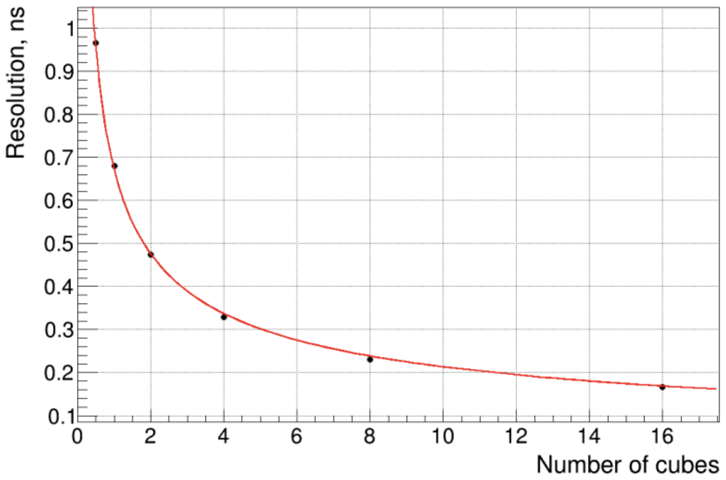
SuperFGD Prototypes tests result

Light yield



Time resolution



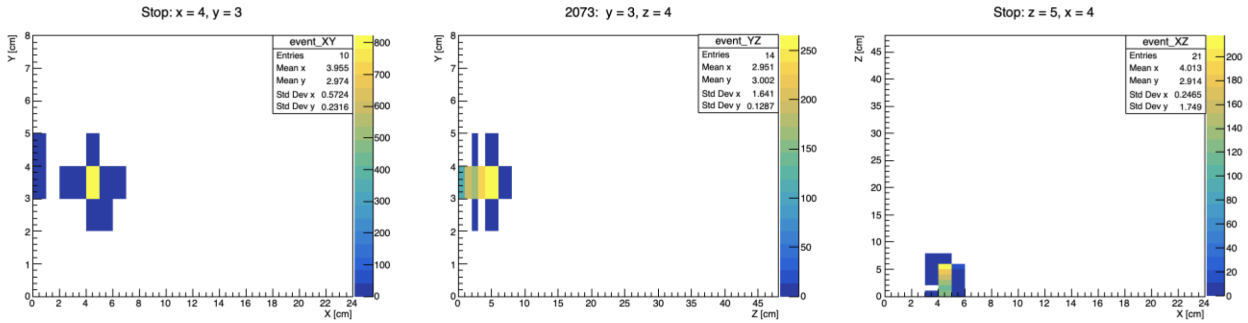


- *A MIP in the SuperFGD has a mean light yield of 50 photoelectrons per cube and per 1 fiber;*
- *The three signal paths (HG, LG and ToT) show similar mean values and standard deviations, which is an indication that calibration was applied correctly.*

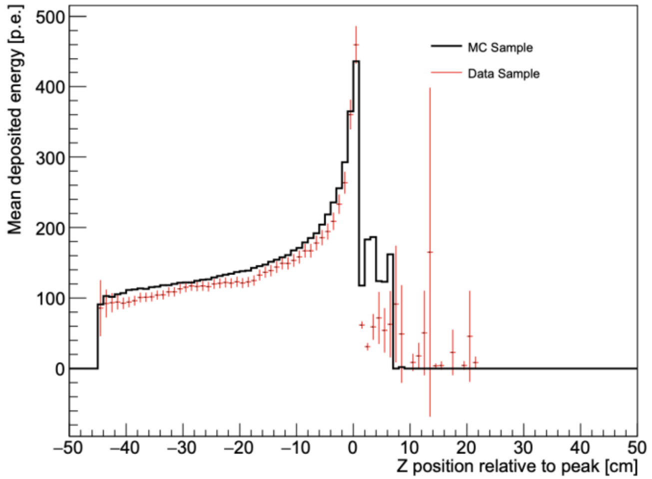
Distribution of the difference between two scintillator cube times in the same event that has σ = 0.96 ns which is √2 times larger than the standard deviation of the one cube time resolution. The cube time is the average of the corresponding times measured with X and Y fibers.

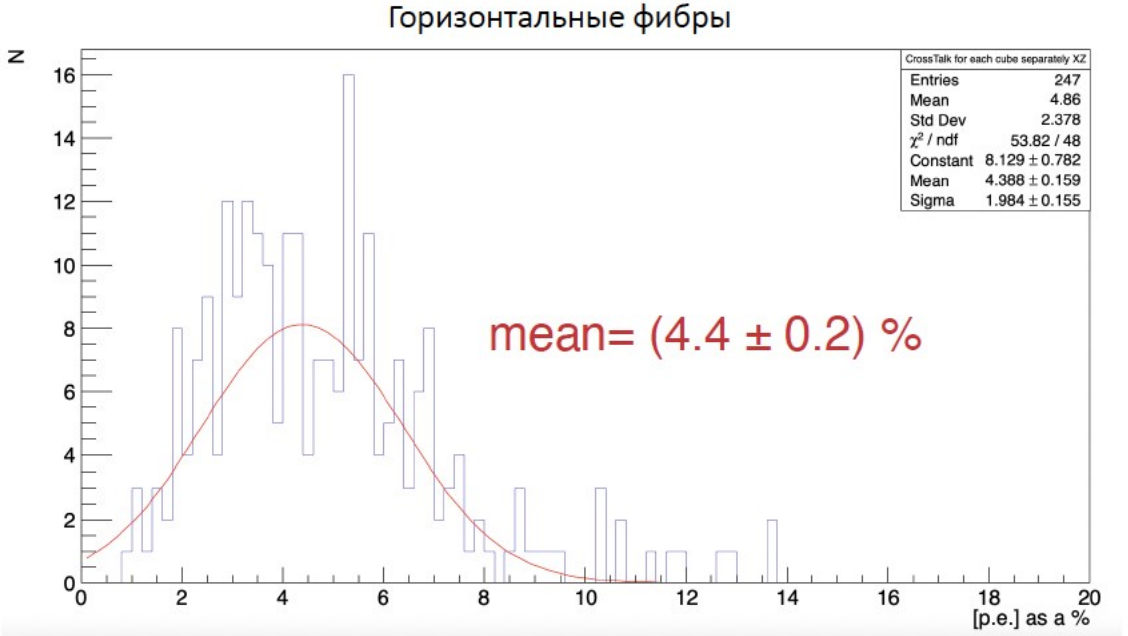
The time resolution dependence on the number of cubes (N) used in the time averaging. In addition, the resolution of a single hit is demonstrated (the first point at N=0.5). The curve clearly demonstrates the $1/\sqrt{N}$ dependence. For the range of cubes fitted (N≤16) the expected constant term is consistent with zero and therefore not included in the fit.

Cross-Talk



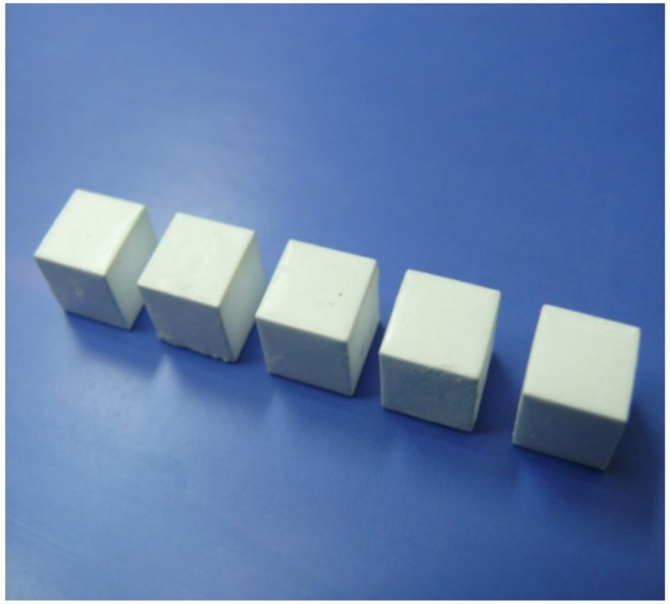
- Cross-Talk was calculated with data from stopped protons.
- Cross-Talk difference between Vertical and Horizontal fibers caused due to Taywek reflector, which was added between scintillator layers.

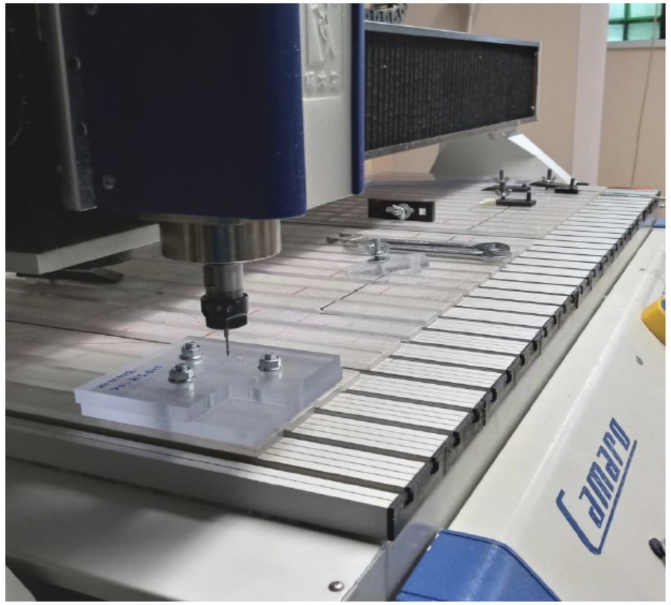




Cube Production

1. Cubes was produced by injection into a mold, 12 cubes at a time (~ 4000-5000 cubes per day).
2. They was etched in a chemical to deposit a reflective layer on their outside that serves to minimize light leakage (Average coating thickness is about 100 μm).
3. Finally, three orthogonal holes was drilled through the cubes. This is the most time-consuming step as it requires high accuracy and can only be done one cube at a time (~12,000 holes per day)



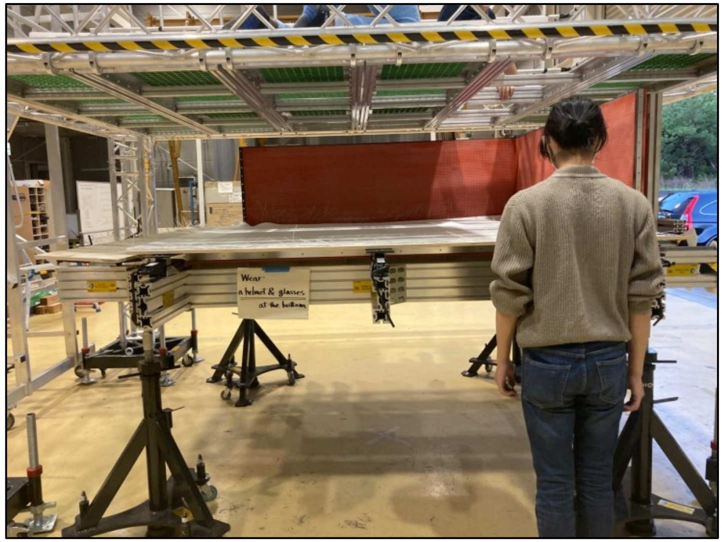


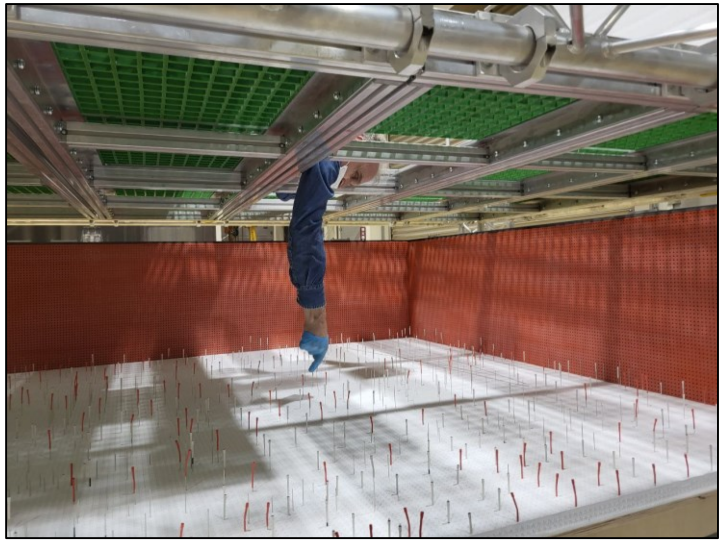
Scintillator Layers Production

- After production, the cubes was sent to INR (Moscow) for assembly.
- Assembly steps:
  - Strings of cubes are pre-assembled using fishing lines of 1.3 mm diameter.
  - These strings are then sewn together to create 2D arrays of cubes.
- The fishing line method provides the flexibility to align and assemble the long arrays of cubes despite the small variation in cube sizes and hole positions.

Super FGD box and assembly table

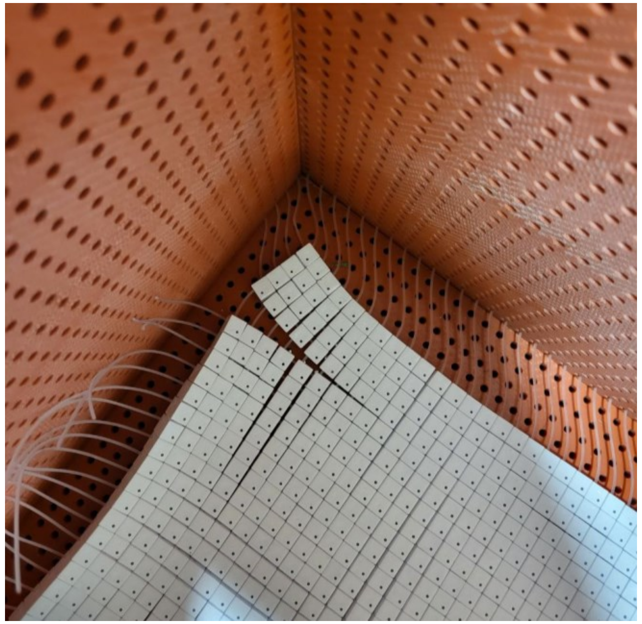
- For Super FGD assembly Assembly Table and Top Access System was prepared.
- Top Access System was needed to to access the central areas of the detector during assembly
- The Assembly table was assembled and fixed to the floor by anchors.
- Three panels of the SuperFGD detector box were installed: Downstream, Bottom and Left panels.
- Construction was carried out in J-PARC NA building.





Scintillator Layers Assembly

- Scintillator layers was assembled one by one. Each layer is 192x184 cm2 and contain 35328 cubes.
- Vertical alignment of cubes holes was done with needles and metallic rods.
- About 20 peoples was involved in cubes assembly.
- Construction was carried out in J-PARC NA building.



Scintillator Layers Assembly

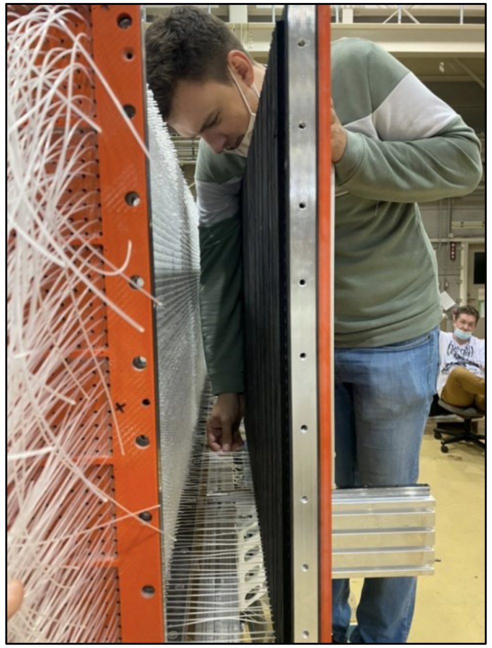
- Special support structure was prepared to control detector horizontal dimensions.
- This system was contains of wood planes and supporting stops.
- Horizontal dimensions were maintained at 1.5 mm.

Scintillator Layers Assembly

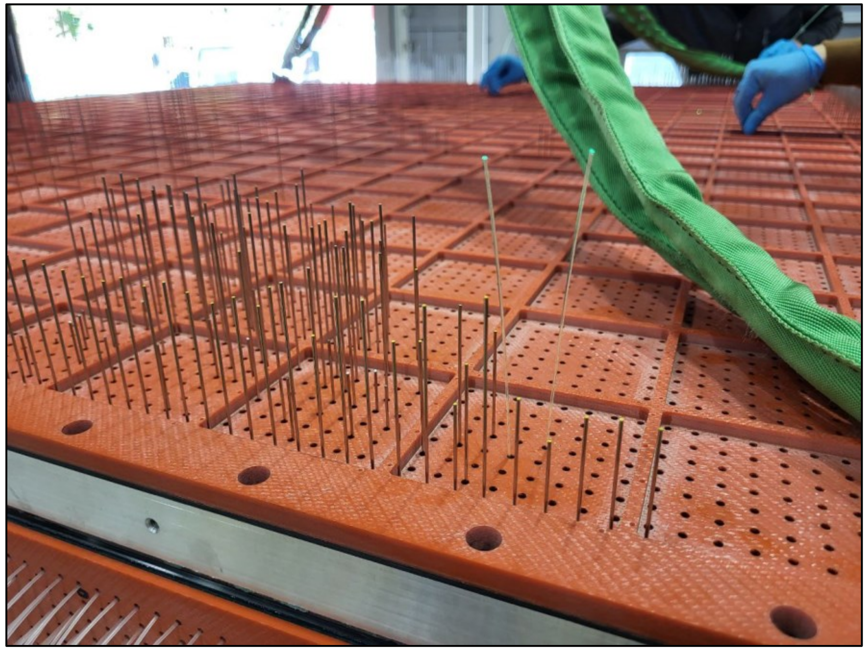
In November 2022, all 56 layers (or two million scintillation cubes) were assembled in J-PARC.

Side panels installation

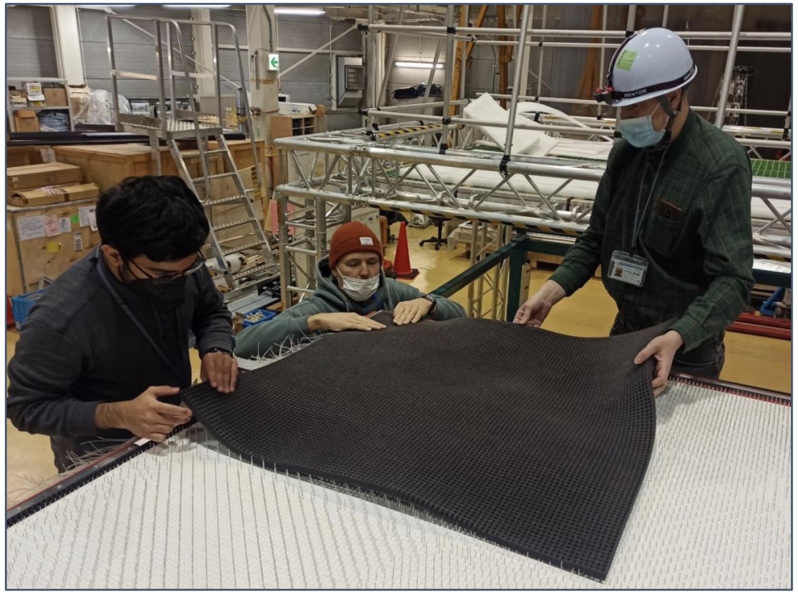
- *Before side panels installation 14000 metallic 1m rods were install for vertical alignment.*
- *4 days was spent to thread each fishing line throw side panel's holes.*

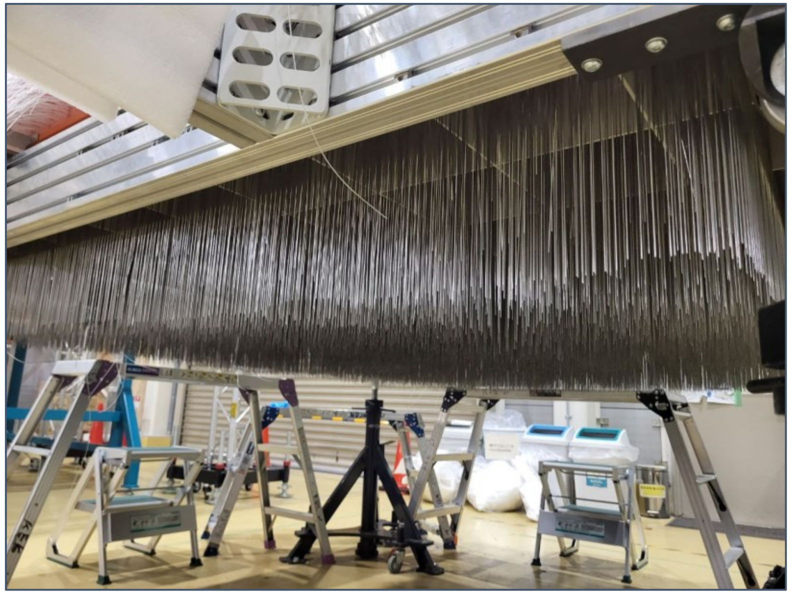


Top panel installation



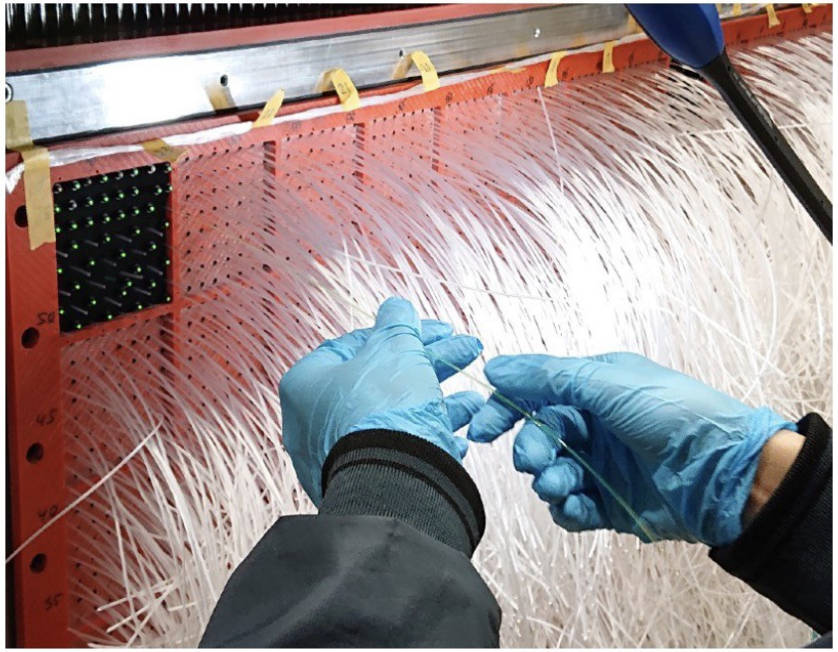
- 2,5 mm foam was installed on metallic roads before top panel installation.
- Vertical alignment was done by using screws and metallic rods.





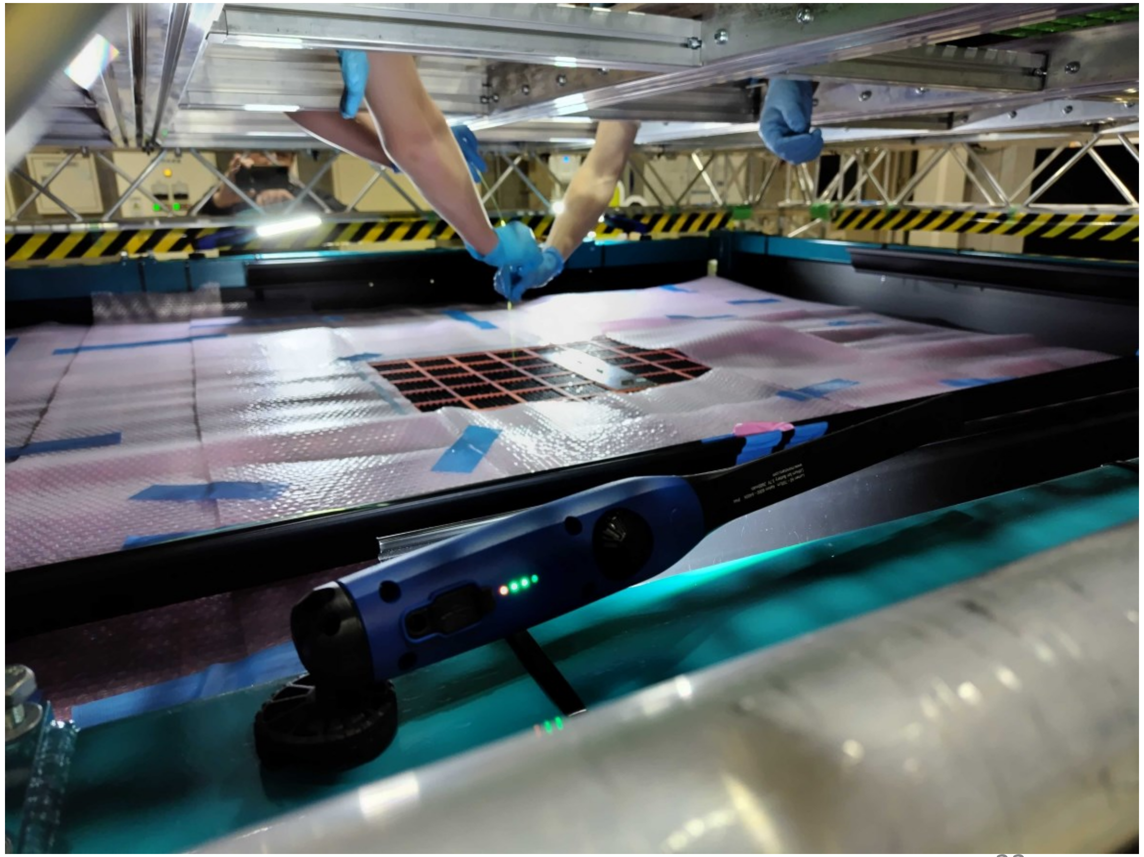
Horizontal fibers installation

- *About 50 people in total was involved in fiber insertion.*
- *Chess pattern was used during fiber insertion.*
- *Fishing lines removal were done from opposite side of detector.*
- *Quality Control was done for each inserted fiber.*
- *Construction was carried out in J-PARC NA building.*



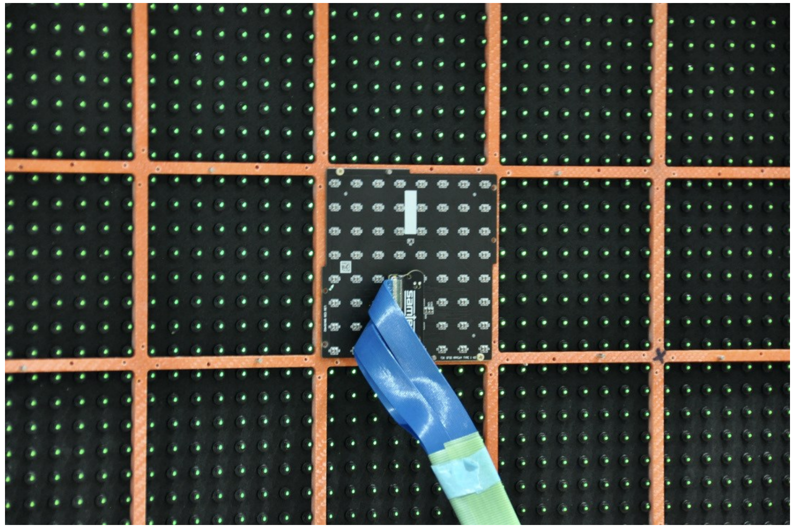
Vertical fibers installation

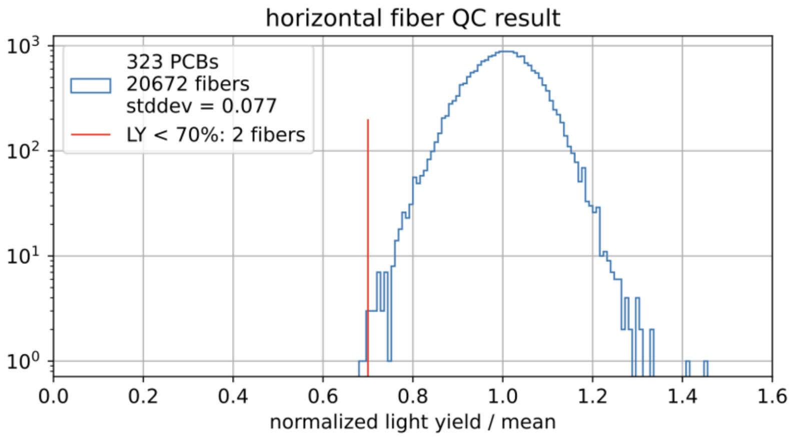
- About 50 people in total was involved in fiber insertion.
- Top access system was used to reach middle part.
- Quality Control was done for each inserted fiber.
- Construction was carried out in J-PARC NA building.

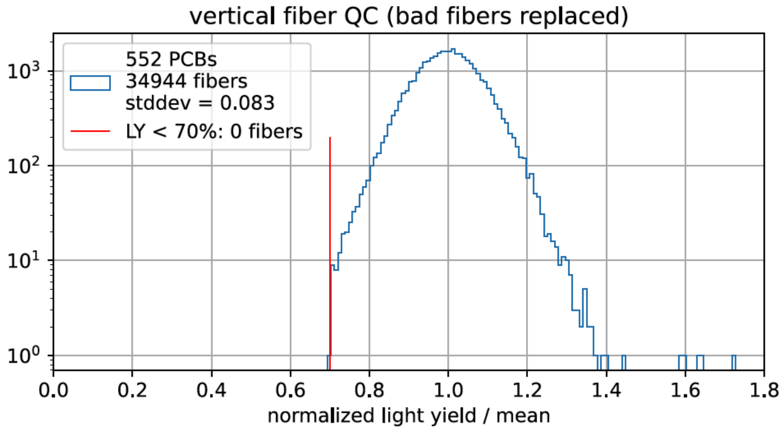


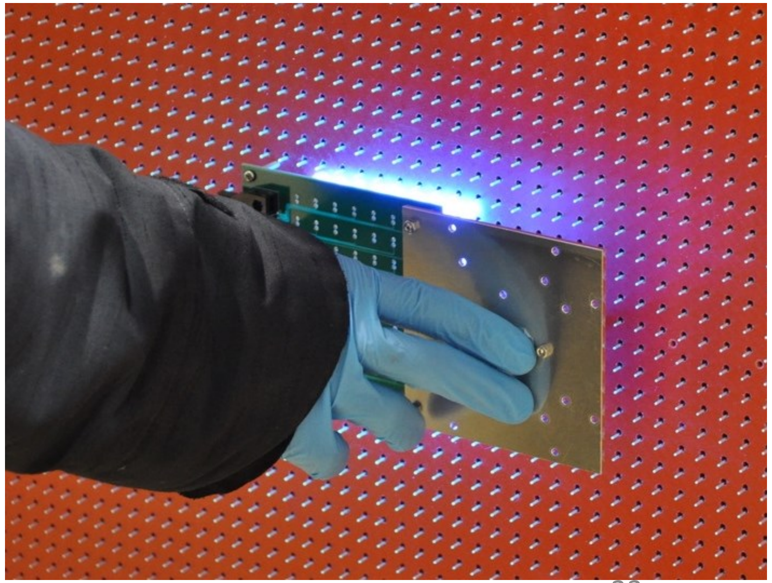
QC fibers tests

- *Quality Control was done for each inserted fiber.*
- *0.3% fibers was qualified as broken.*
- *0,1% of fibers was damaged during installation due to falling on the floor.*
- *All broken fibers was replaced.*





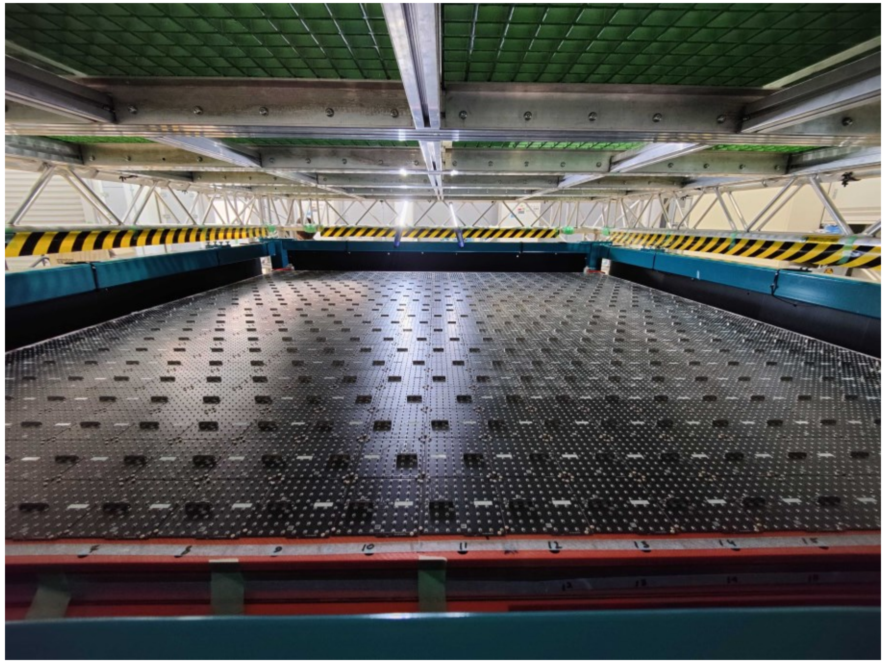


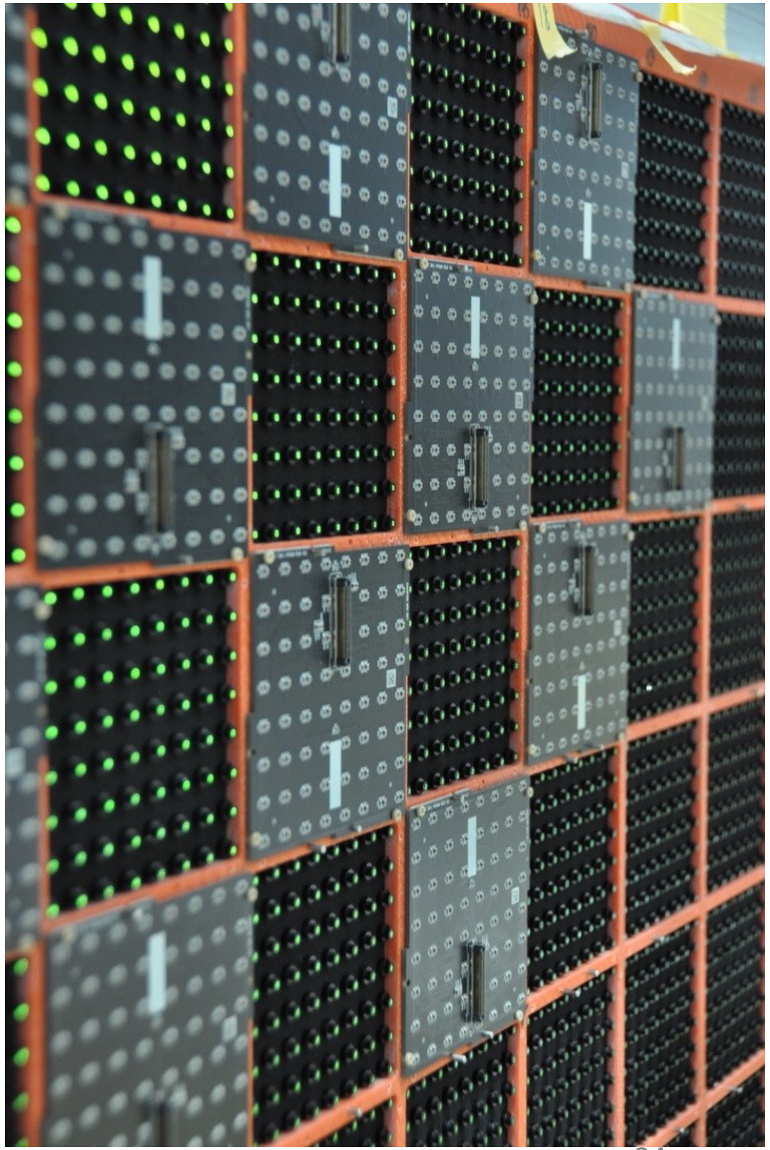


MPPCs PCBs

Table 1: Requirements of the MPPC Characteristics

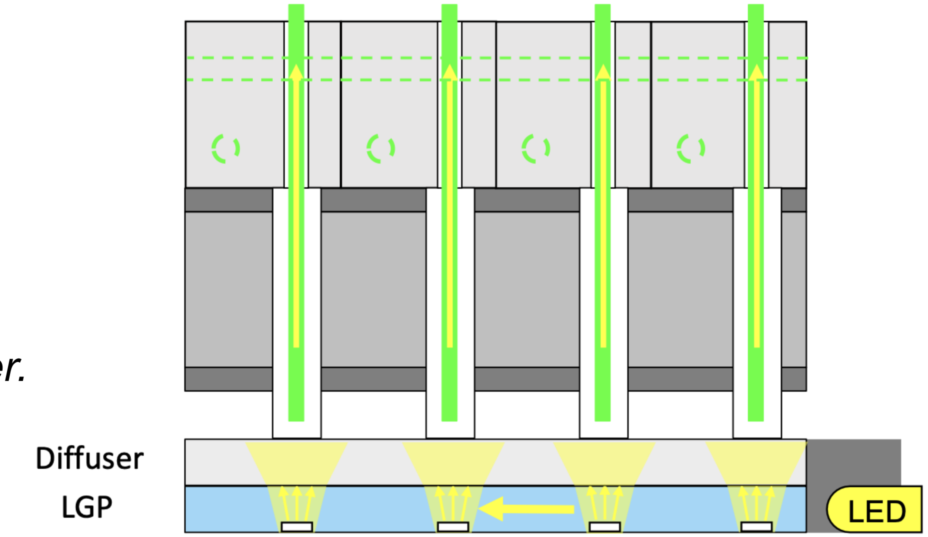
Item	Requirements
Gain	variation $\leq$ 12%
Relative PDE	variation $\leq$ 10%
Breakdown voltage	range within 2.5 V in each PCB
Dark Noise rate	$\leq$ 200 kHz
Crosstalk probability	$\leq$ 3%

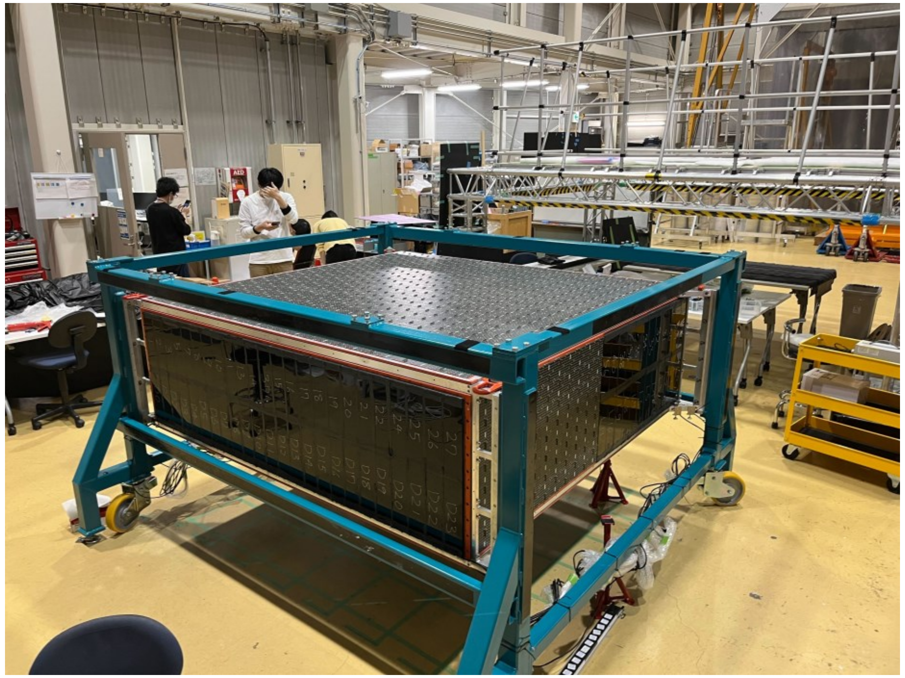




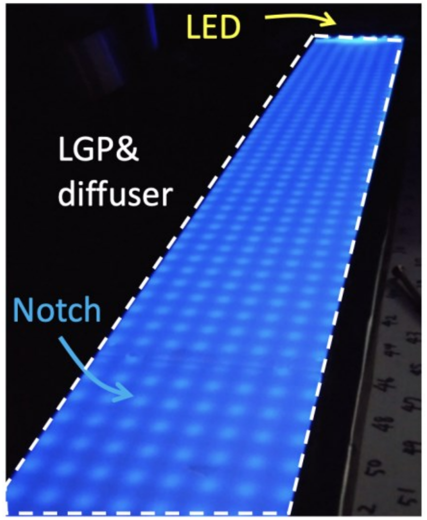
Calibration system

- *For MPPCs calibration special LED system was designed.*
- *This system is contain LED driver, LED, Light guide panel and diffuser.*



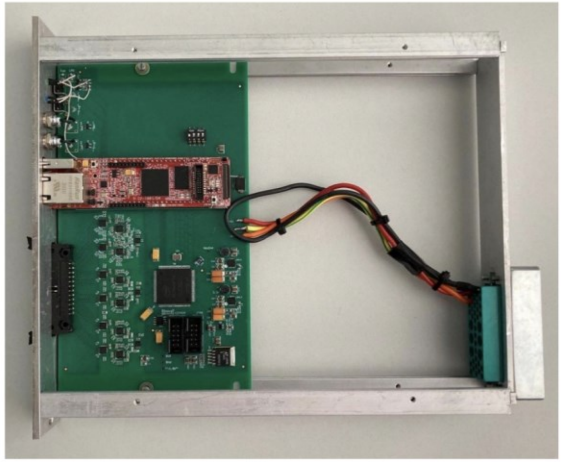


<TMU/KEK> LGP module



LGP module distributes LED light to all MPPCs

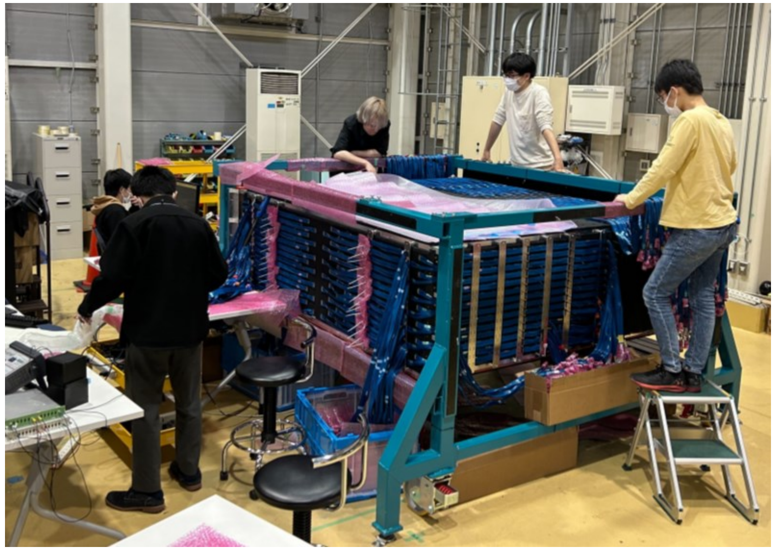
<JINR> LED driver



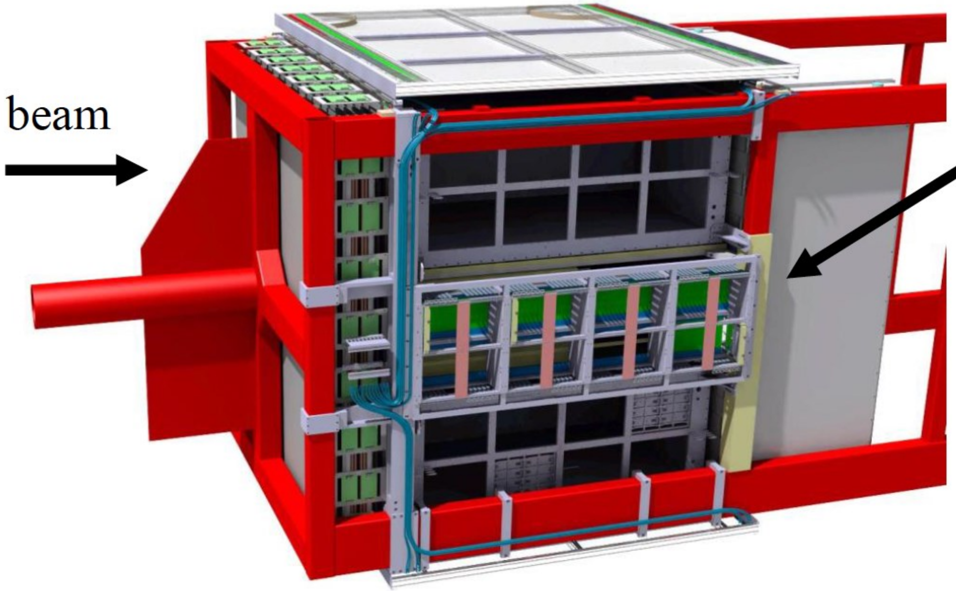
LED driver is pulse generator to drive LGP module

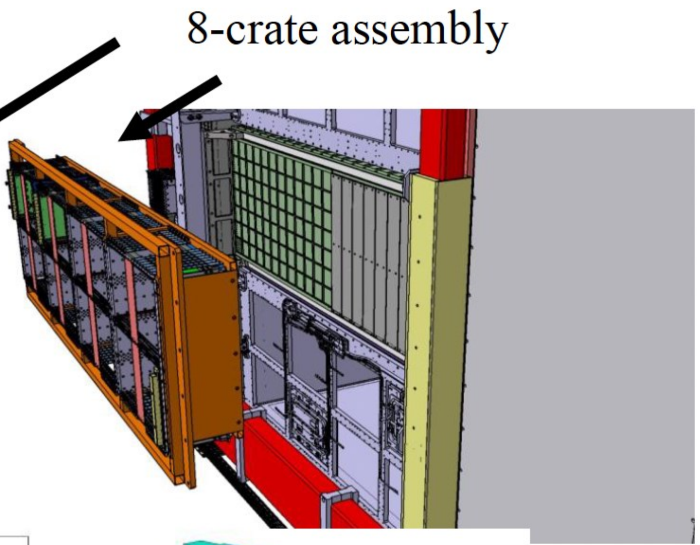
Cabling

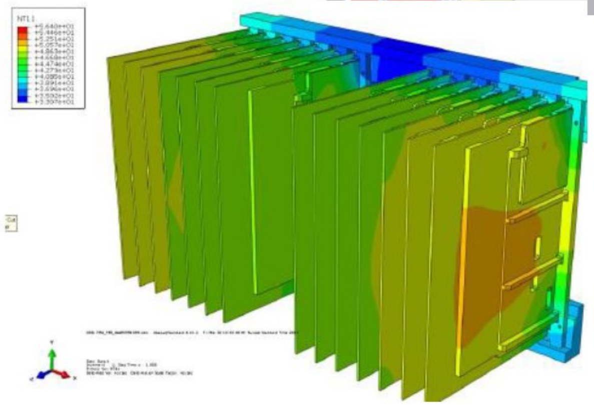
- *About 900 cables with different cable length was labelled and connected to MPPCs PCBs.*
- *Different cable length will give us different delays.*

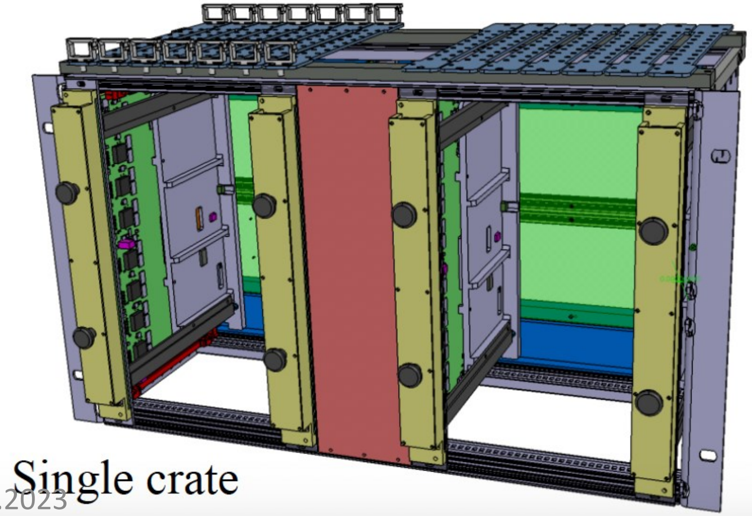


Electronics



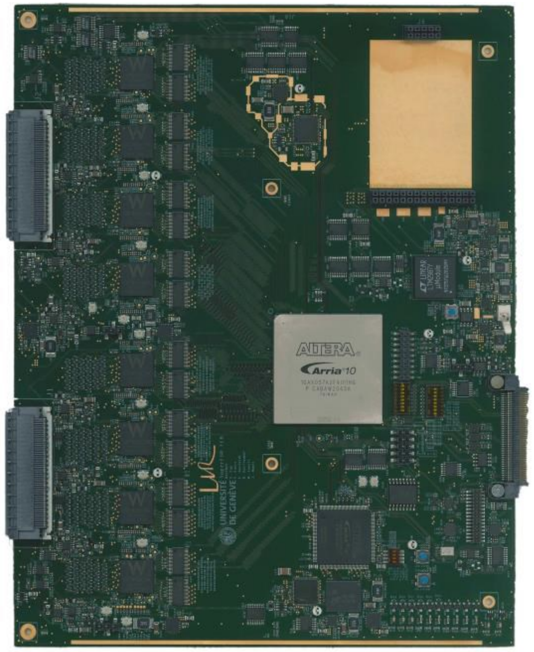




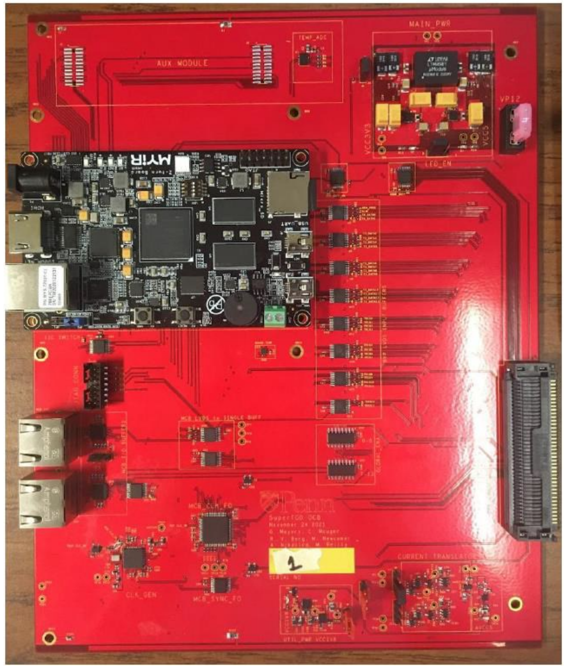


- *16 crates – 8 on each side of the detector*
- *Single crate – 14 Front-end boards, Optical Concentrator Board, Backplane, Power distribution*
- *Thermal model built to ensure < 60 degrees C*

Electronics

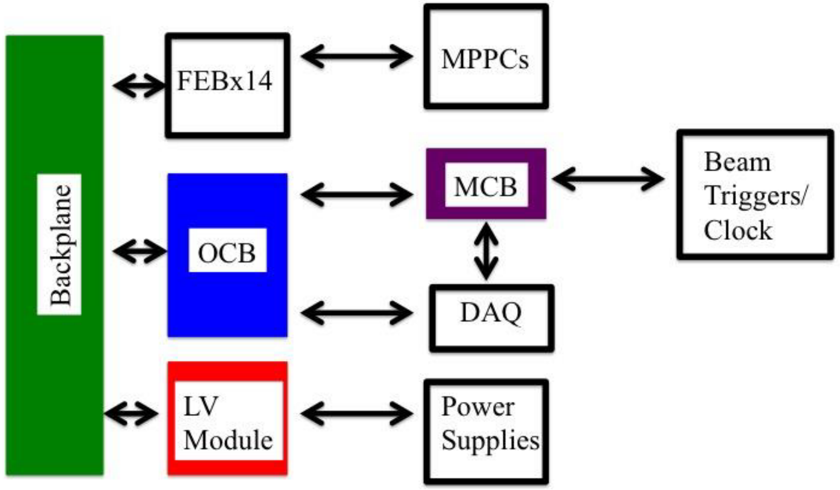


Front-End Board (14 boards per crate) – analog processing, ADC, bias voltage to the MPPCs 8 CITIROC chips per board – 256 channels



Optical Concentrator Board (1 board per crate) –initial data aggregation, switchyard to outside world

SFGD Electronics Architecture



Master Clock Board –external to magnet, hardware connections to the beam triggers

Status and Plans

- *Construction phase was successfully finished.*
- *Commissioning is ongoing at J-PARC.*
- *Commissioning plan:*
  - *Assembly and tests of electronics*
  - *DAQ development and tests;*
  - *Calibration development and tests;*
  - *Calibration;*
  - *Cosmics tests on surface;*
  - *Installation into the ND280 magnet*
  - *Test in the ND280 pit;*
  - *Collect the first neutrino events in the Fall of 2023*

Summary

- 3D highly segmented neutrino detector SuperFGD

will be the central part of the near detector complex of T2K experiment

- It is the key element for sensitive search for CP violation in T2K and HyperK

- T2K goal to establish CP violation at 3σ level

- Goal of T2HK with far detector HyperKamiokande: discovery of CP violation and measurement of δ_{CP}

- SuperFGD construction is completed
- SuperFGD commissioning is ongoing
- Calibrations system is tested
- Electronics production and tests are in progress
- DAQ development is in progress
- Installation of SuoperFGD into ND280 magnet is planning in September 2023
- First run with neutrino beam is expected in the Fall of 2023