The 06th Technology and Instrumentation in Particle Physics (TIPP 2023) conference

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Segmented scintillator neutrino detector SuperFGD for T2K experiment

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(On behalf of the SuperFGD group)

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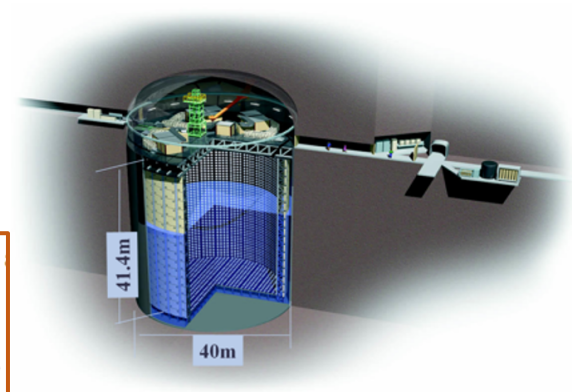
05.09.2023

T2K experiment ("Tokai to Kamioka")

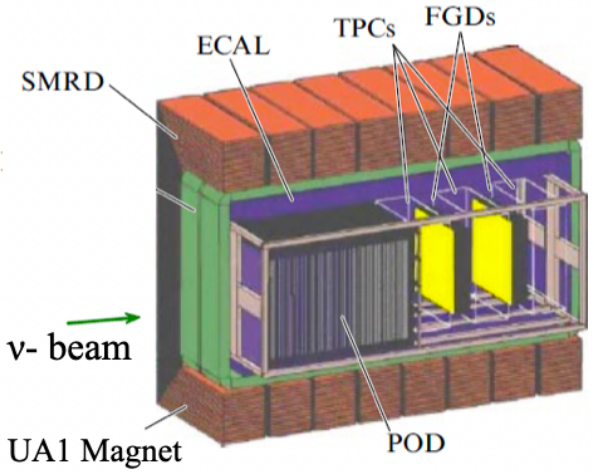
The main experiment goals:

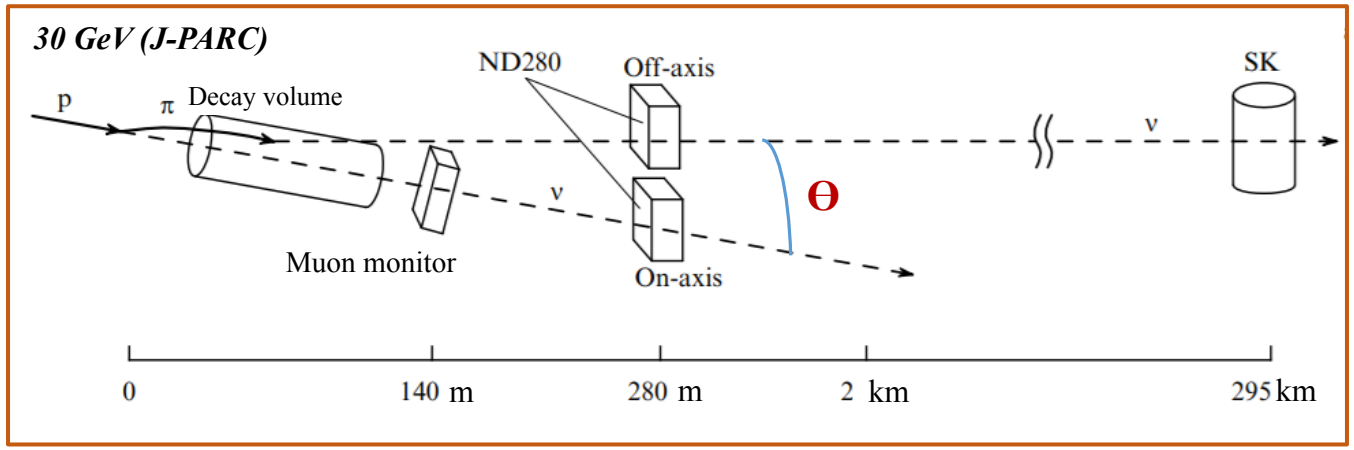
- precision measurements of the oscillation parameters with ν_μ ($\overline{\nu}_\mu$) beam;
- search for CP violation in neutrino sector

Super-Kamiokande



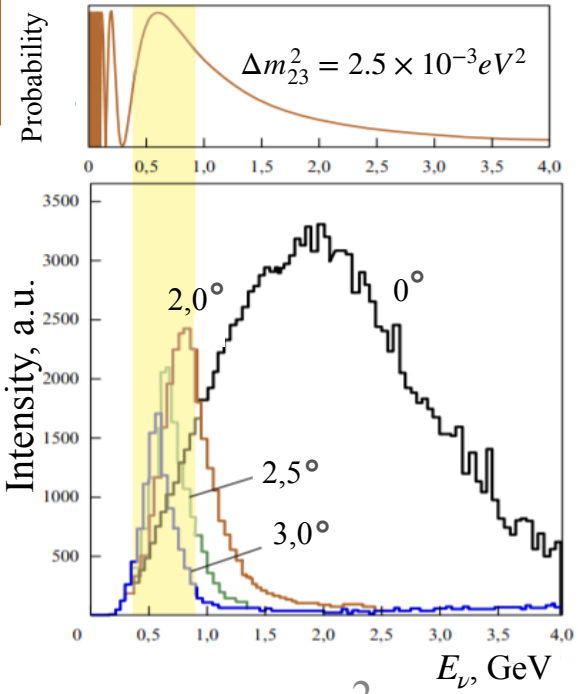
Near off-axis ν-detector (ND280)

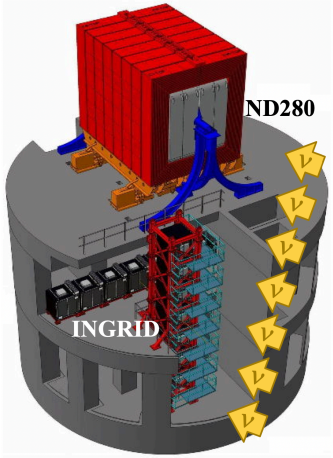




T2K experiment scheme

Off–axis ν-beam





μ-monitor of the ν-beam on-axis (INGRID)

In the first oscillation maximum:

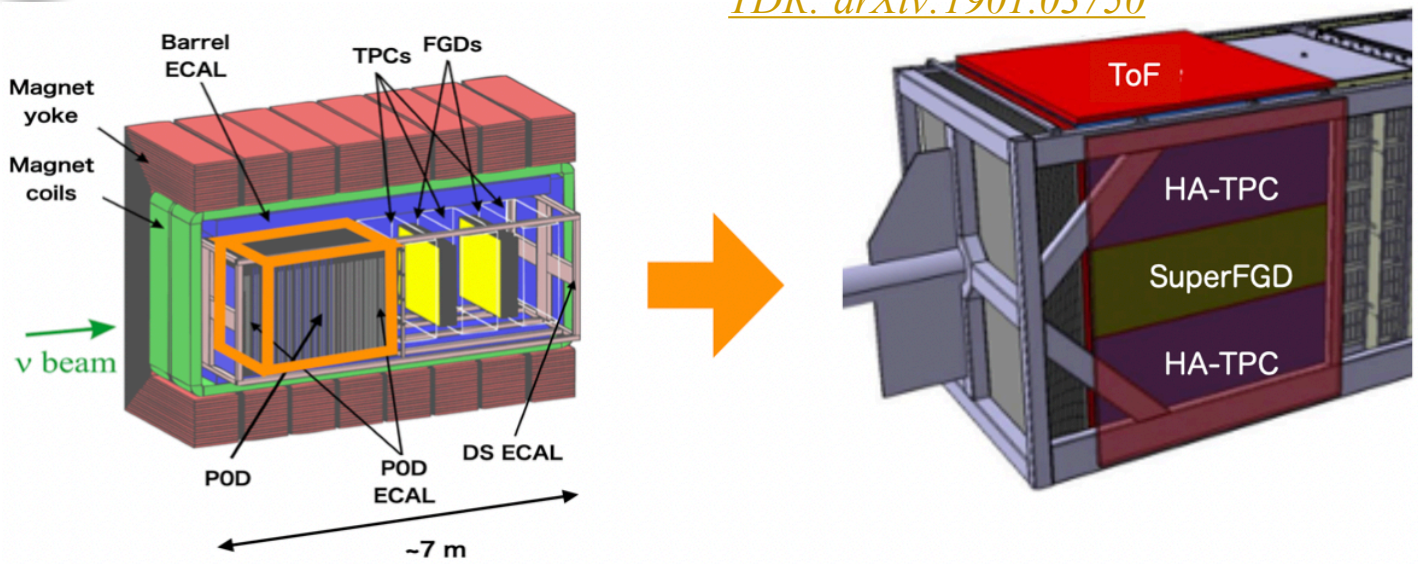
at $\angle\,\Theta = 2.5°$ ➡ $E(\nu)_{max} = 0.6$ GeV

to improve a sensitivity to δ_{CP}

we need to reduce systematic uncertainties

Motivation for ND280 Upgrade

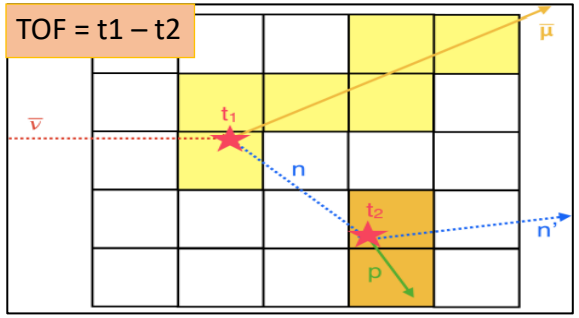
TDR: arXiv:1901.03750



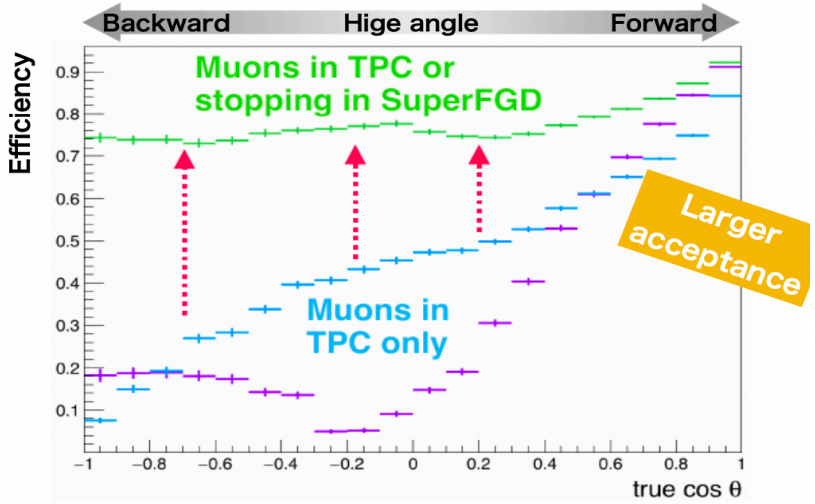
New upstream tracker:

- 2 × High-Angle TPC (Covering large acceptance)
- 1 × SuperFGD (Target & tracking detector)
- 6 × Time-of-Flight (Veto, Particle ID, Cosmic calibration trigger)

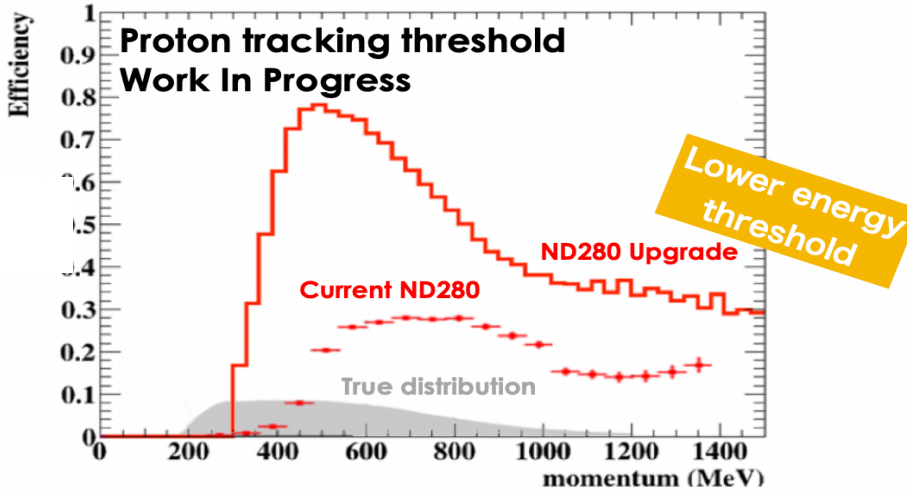
- detection of neutrons:



- 4π-acceptance for charged particles



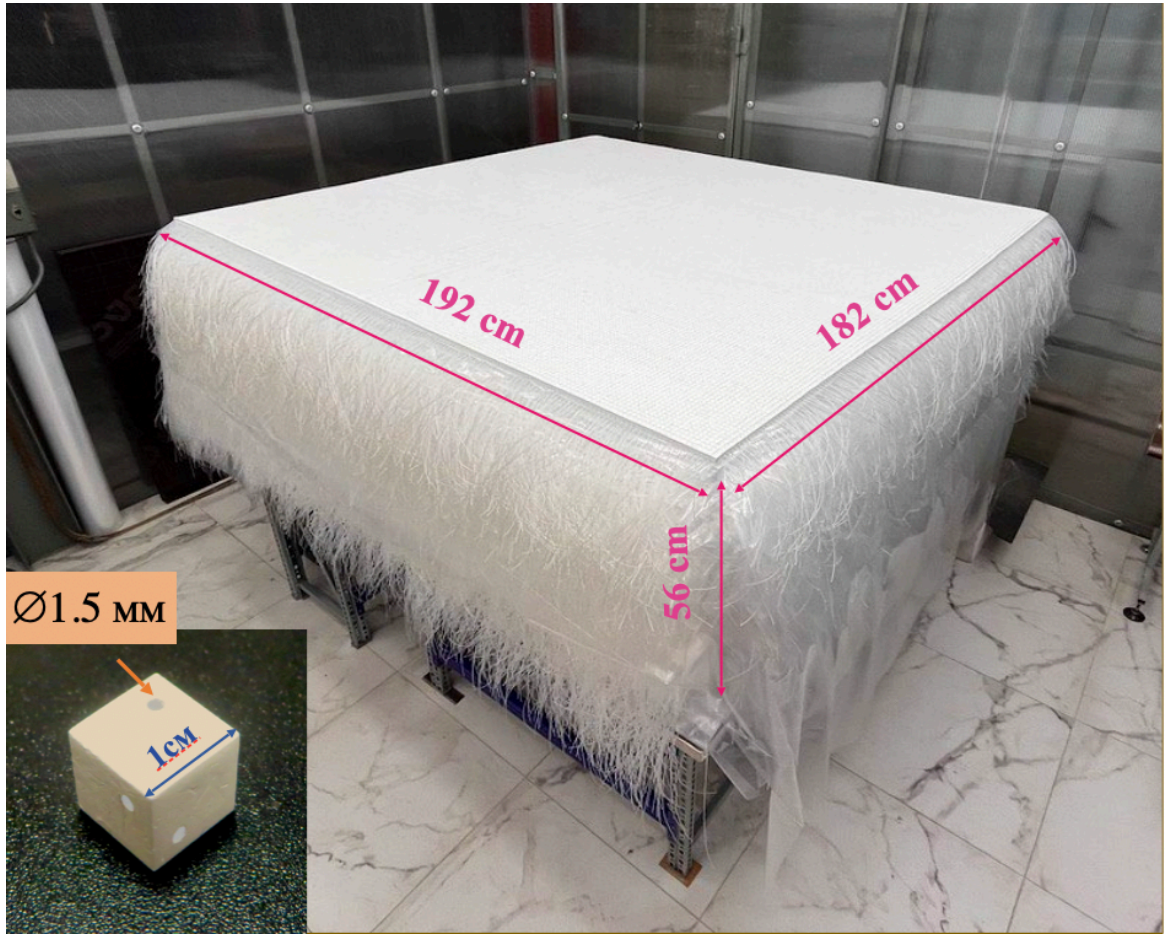
- a low threshold for proton and pion detection



- an electron/gamma separation

Expected result: Reducing of systematic error in T2K to the level of 3-4%

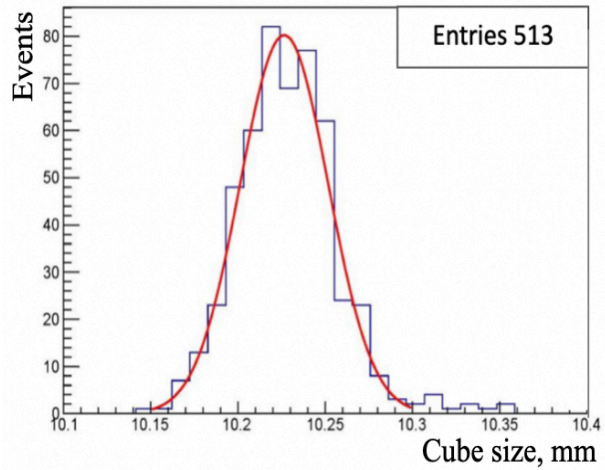
SuperFGD (Super Fine-Grained Detector)



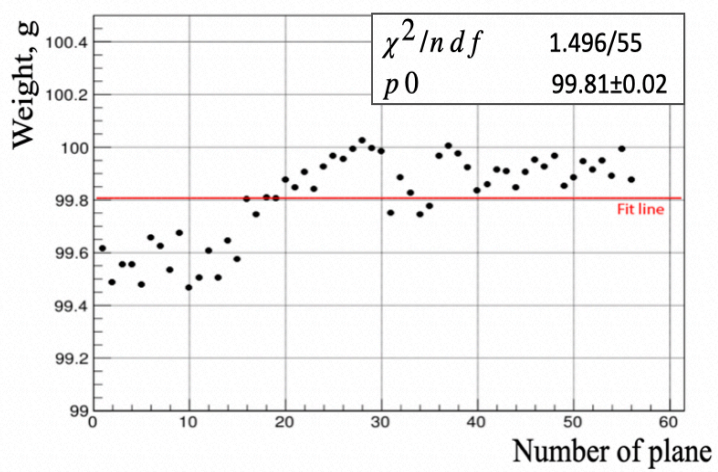
- Detector size: **192(*x*)×182(*z*)×56(*y*) cm^3**
- **1,956,864** optically-isolated plastic scintillator cubes of $1 \times 1 \times 1$ cm^3
- Three orthogonal through holes ∅1.5 mm in each cube
- **56,384** readout channels for:
  - Wavelength Shifting (WLS) fibers ∅1 mm Kuraray Y11 (200) multiclad S-type
  - Hamamatsu Photonics MPPCs S13360-1325PE series
- Detector active mass ~ 2 tons

Cubes manufacturing

- Vladimir, Russia (UNIPLAST Co.)
- Cubes size: $10 \times 10 \times 10$ mm^3
- Material: polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of 1,4-bis benzene (POPOP)
- Method: injection molding
- White reflective layer: 50–80 μm thick
- Holes for WLS fibers: three in each cube, ∅1.5 mm

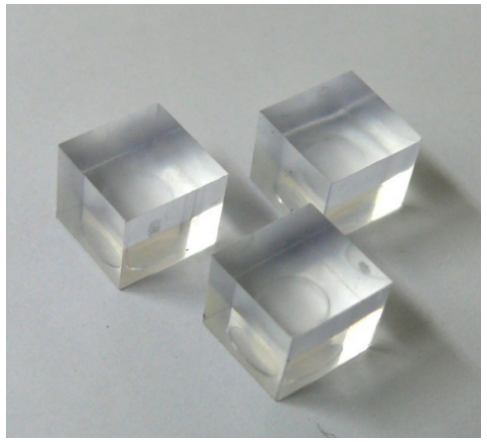


Cube side size:
10.23 ± 0.025 mm

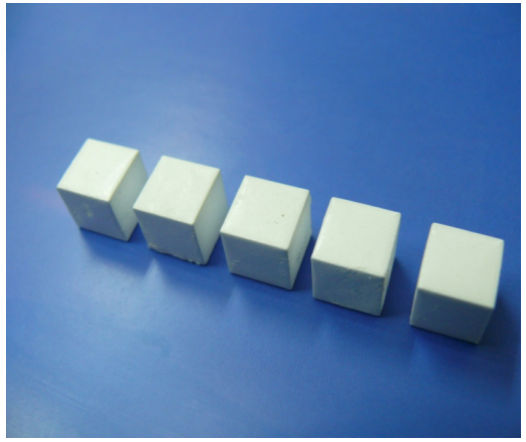


Weight of a single cube:
0.9977 ± 0.0002 g

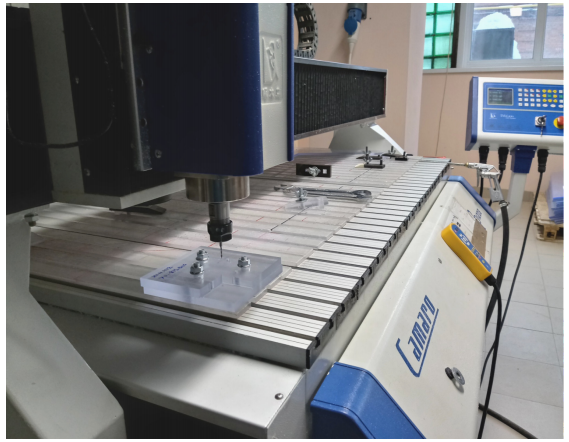
injection molding method



etching in a chemical substance (a reflective layer formation)

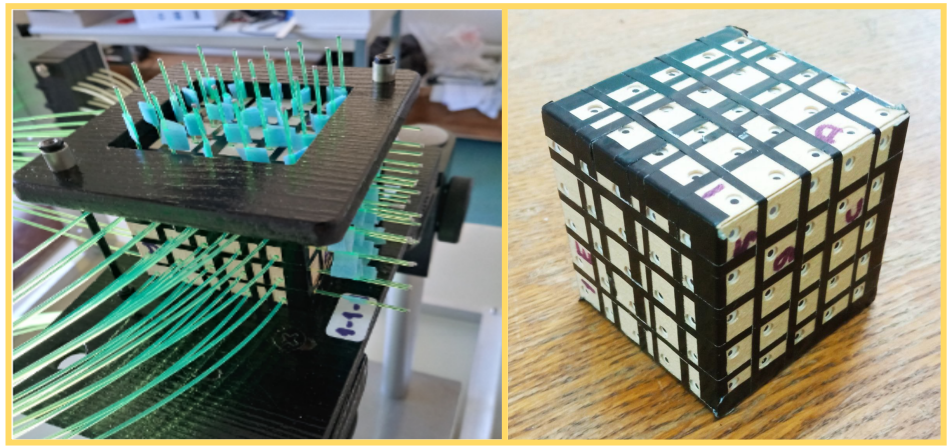


drilling three orthogonal through holes in each cube



The 1st SuperFGD prototype. Test results

The 1st SuperFGD prototype $5 \times 5 \times 5$ cm^3 has been tested on a charged particle beam ($\mu^+/\pi^+, p$) with 0.6 GeV/c at CERN



75 readout channels
WLS + MPPCs
WLS fibers: Kuraray Y11(200) S-type, ⌀1mm, 1.3 m length
MPPCs: Hamamatsu 12571-025C with a 1 × 1 mm^2 active area and 1600 pixels

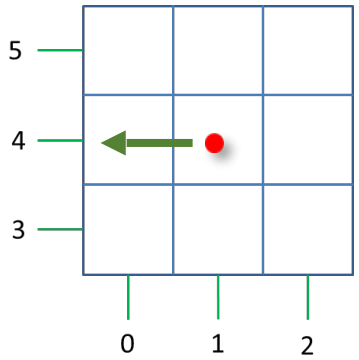
125 cubes with 3D optical reading

Nucl. Instrum. Meth. A 923 (2019) 134-138
arXiv: 1808.08829

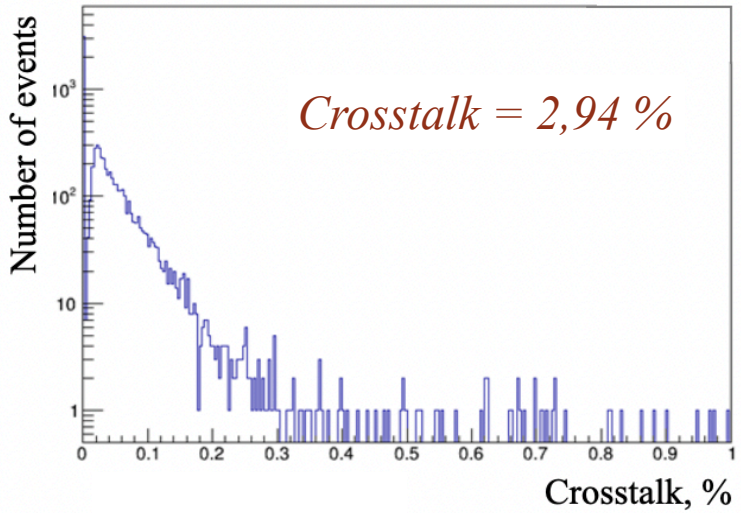
The main SuperFGD cubes parameters:

1. Typical **light yield** per one (several) fiber(s)
   < L.Y.> ≈ **41.0 p.e.** per a fiber /MIP
   < L.Y.> ≈ **79.8 p.e.** per two fibers (a cube) /MIP

2. Average **time resolution** per one (several) fiber(s)
   $< \sigma_t >$ = **0.86 ns per a fiber**
   $< \sigma_t >$ = **0.69 ns per a cube** (two fibers)
   $< \sigma_t >$ = **0.54 ns per two cubes** (four fibers)



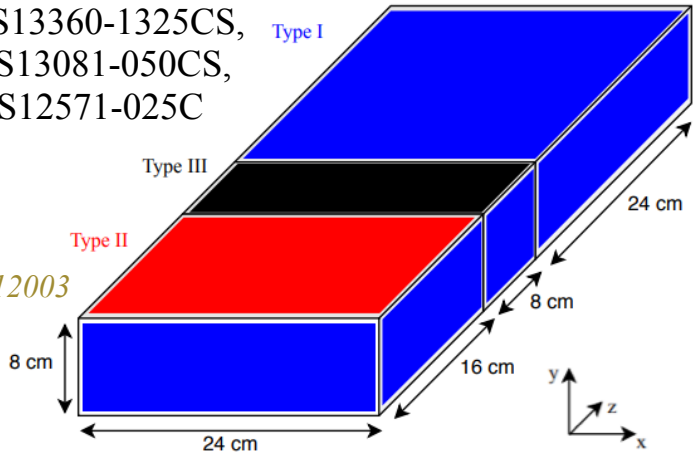
Crosstalk = $\left(\frac{LY_{ch0}}{LY_{ch1}} \right)$



The 2nd SuperFGD prototype. Test results with protons

The 2nd SuperFGD prototype $24 \times 8 \times 48$ cm^3 (9,216 cubes and 1,728 readout channels) has been tested on a charged particle beam with momentum of 0.4 - 8 GeV/*c* at CERN

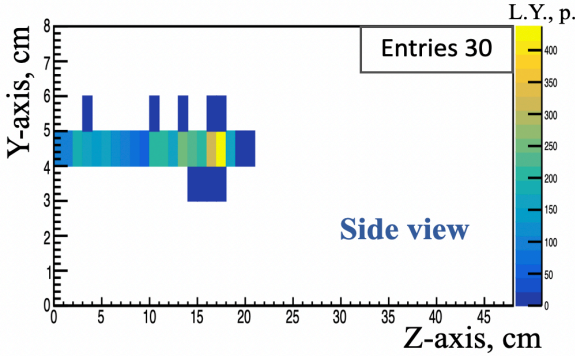
1,152 – **Type I** S13360-1325CS,
384 – **Type II** S13081-050CS,
192 – **Type III** S12571-025C

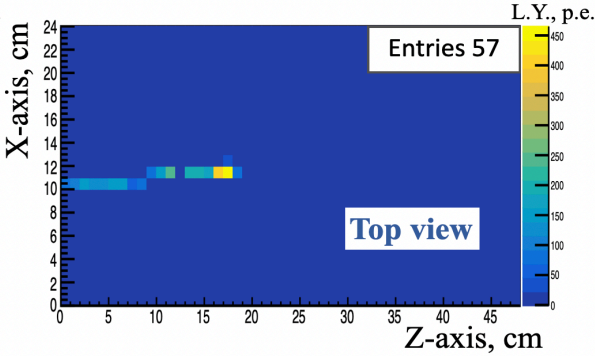


JINST 15 (2020) P12003
arXiv: 2008.08861

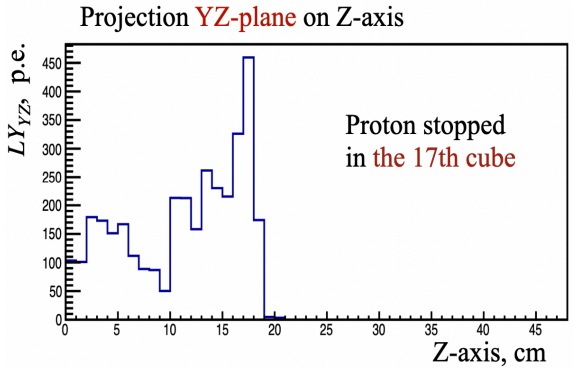
The partially instrumented 2nd SuperFGD Prototype bottom face

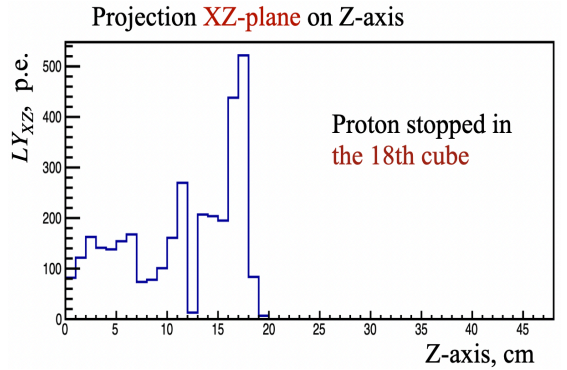
Proton stopped inside the SuperFGD volume





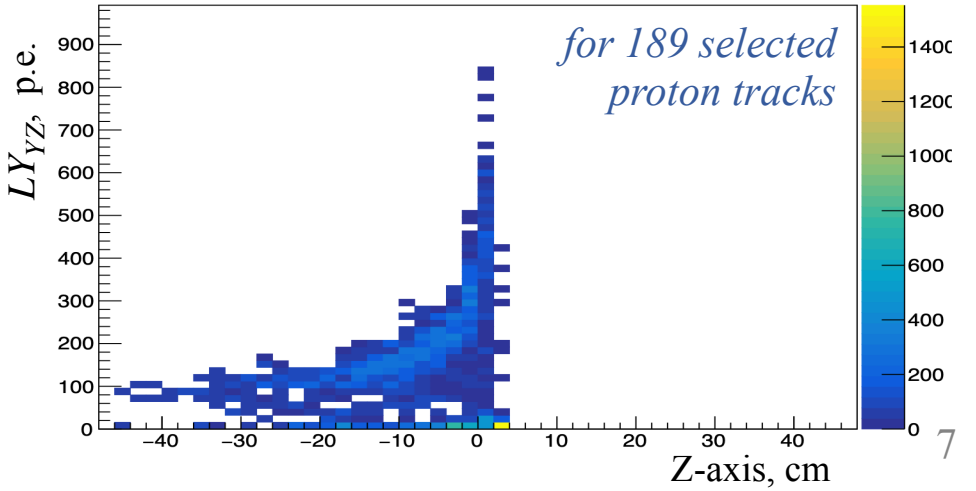
Light Yield distribution





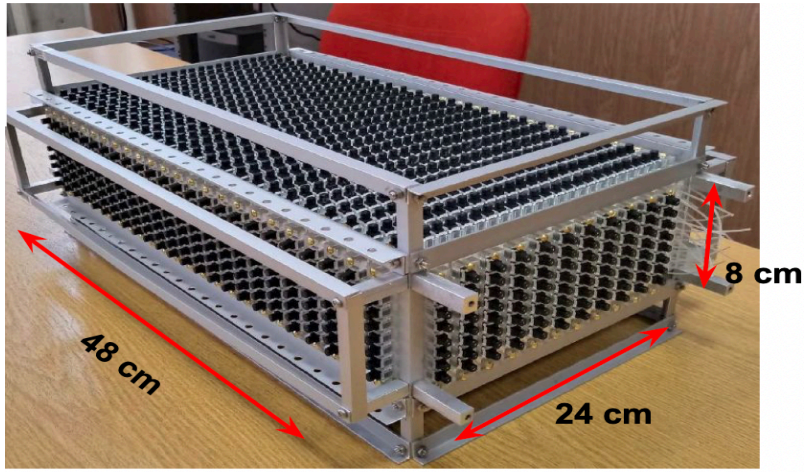
Light Yield distribution **relative to the proton stop point**

$p = 0.5$ GeV/*c*
B = 0.2 T



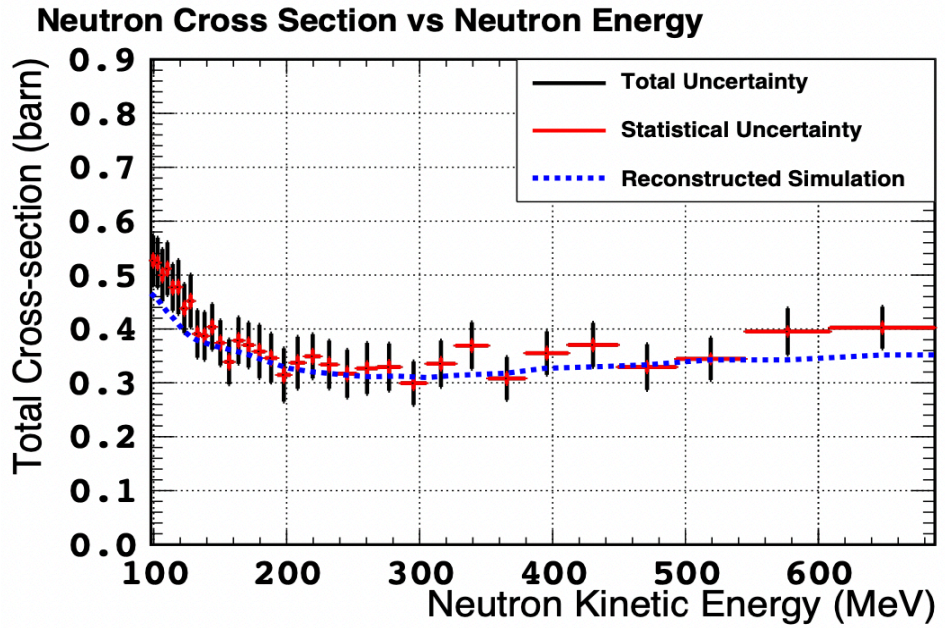
Neutron beam tests at LANL

Two SuperFGD prototypes have been exposed to the neutron beamline at Los Alamos National Laboratory (LANL) in both 2019 and 2020, with neutron energies between 0 and 800 MeV



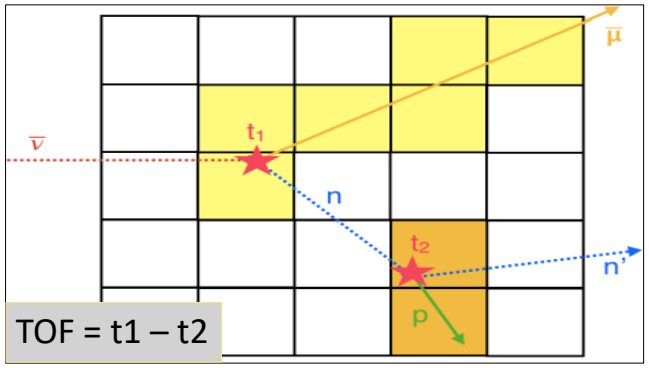
SuperFGD prototype ($24 \times 8 \times 48$ cm^3)

US-Japan prototype ($8 \times 8 \times 32$ cm^3)



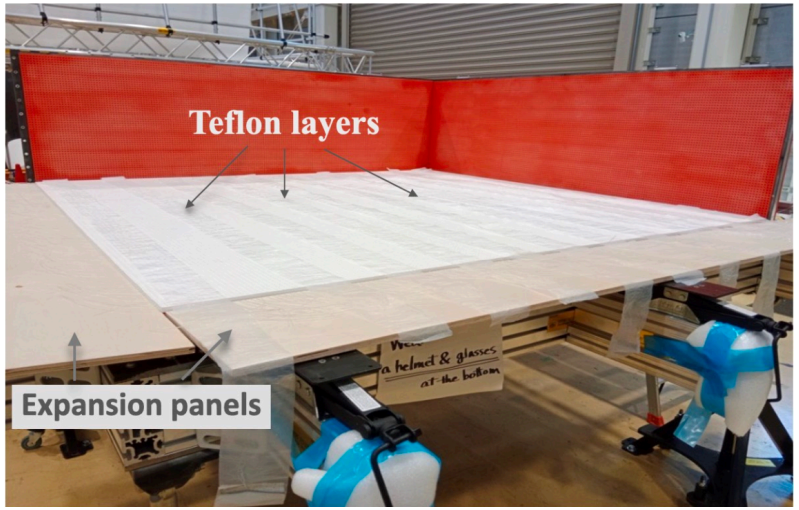
Phys. Lett. B. 840 (2023) 137843
arXiv: 2207.02685

The total neutron cross section on hydro-carbon as a function of neutron kinetic energy

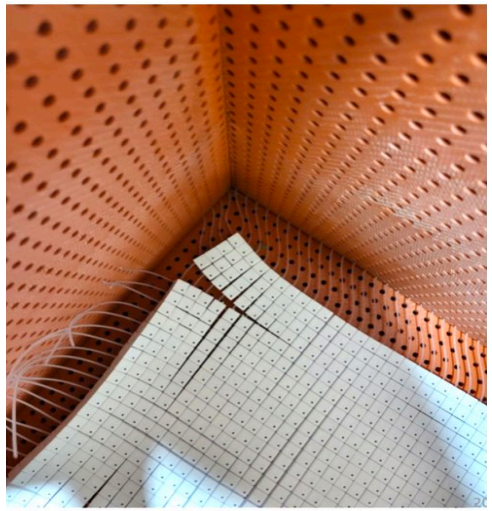


The measured total neutron cross section in scintillator between 98 and 688 MeV is 0.36 ± 0.05 barn

Assembling of the SuperFGD detector at J-PARC (Tokai, Japan)

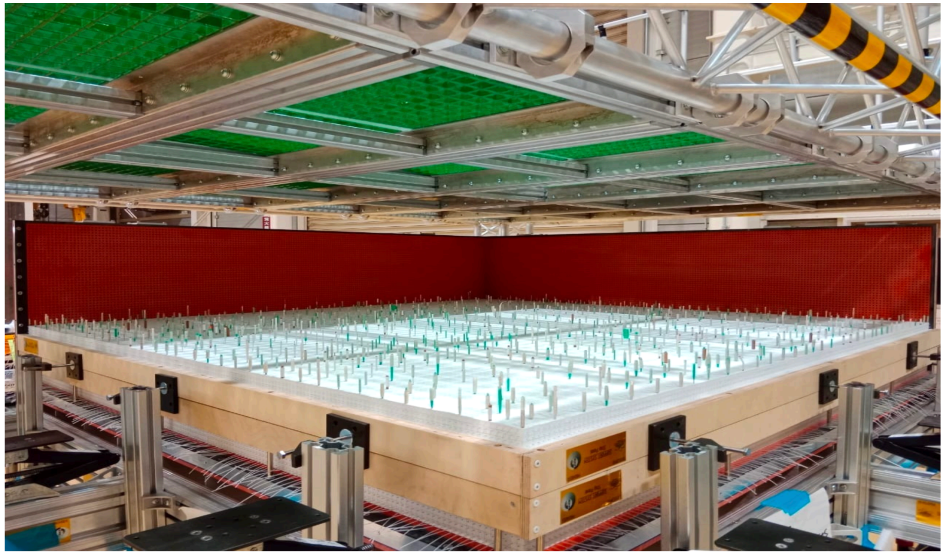


Assembling preparation



First SuperFGD cubes layer

SuperFGD Assembling Platform

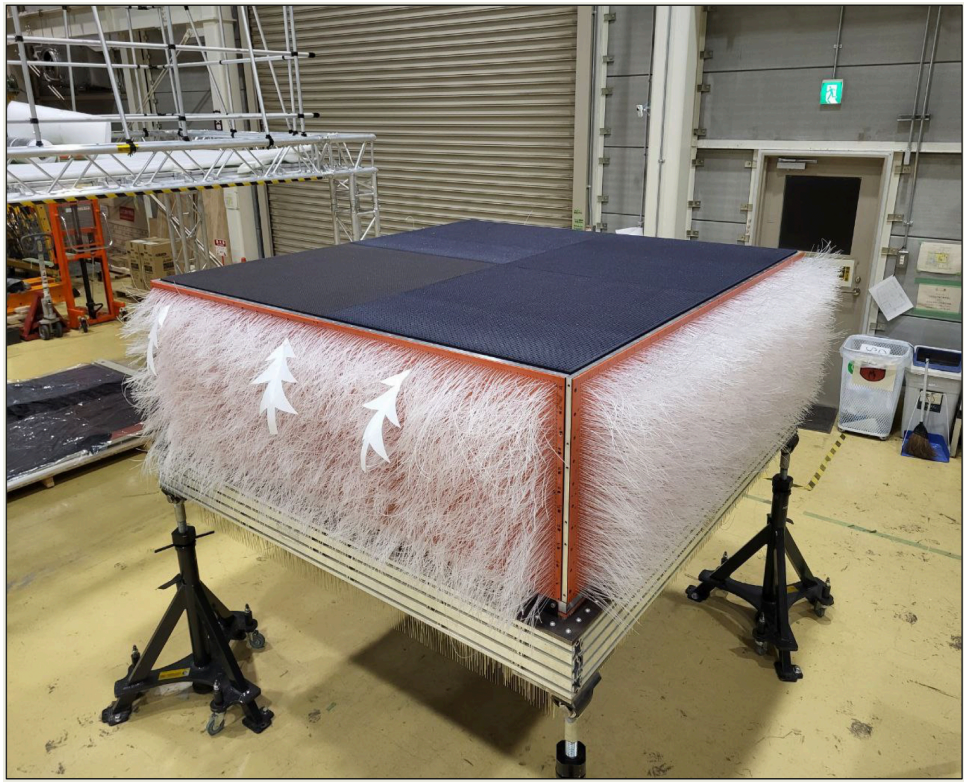


Alignment of the cubes holes with steel spokes (~1000, 20 cm, ∅1.3 mm) and stop panels

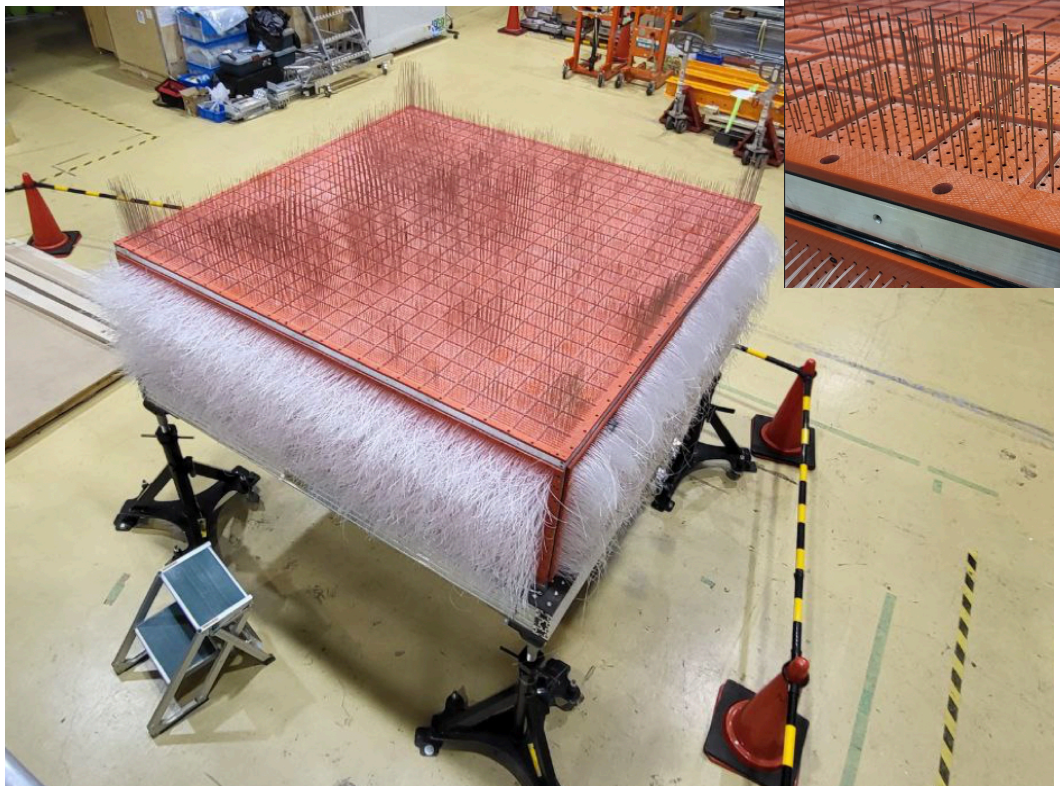
MDPI Physics 2023, 5(3), 690-703

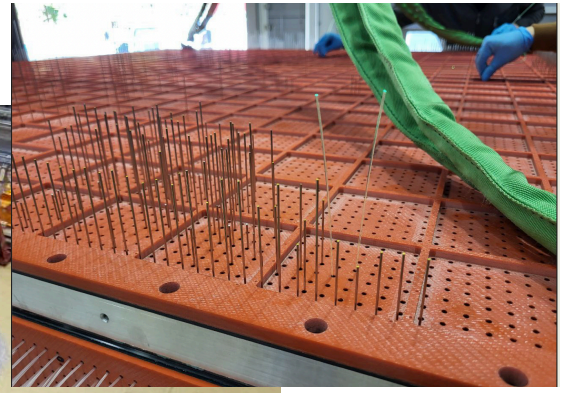
Assembling of the SuperFGD detector at J-PARC (Tokai, Japan)

Before the Top panel installation



Alignment of holes after installation with welding rods (~ 12k, 94 cm, ∅1.2 mm)





SuperFGD transportation to the miniBabyBasket

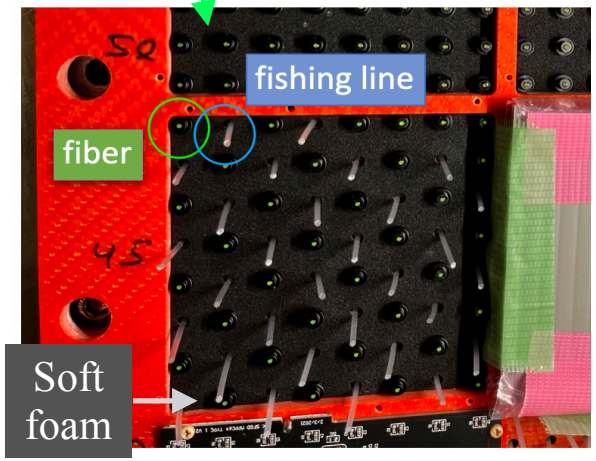
Dismantling of the SuperFGD from the support system

SuperFGD mechanical box with layers of cubes inside the mini Baby-Basket frame

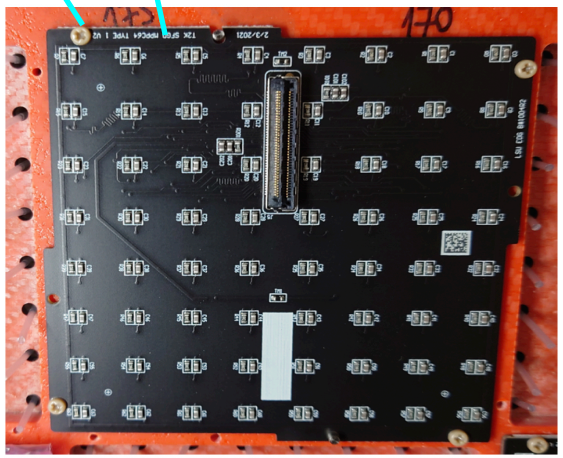
WLS fibers installation

56k WLS fibers ∅1 mm in place of:
- fishing lines (~21k, ∅1.3 mm)
- welding rods (~12k, ∅1.2 mm)

Upstream panel

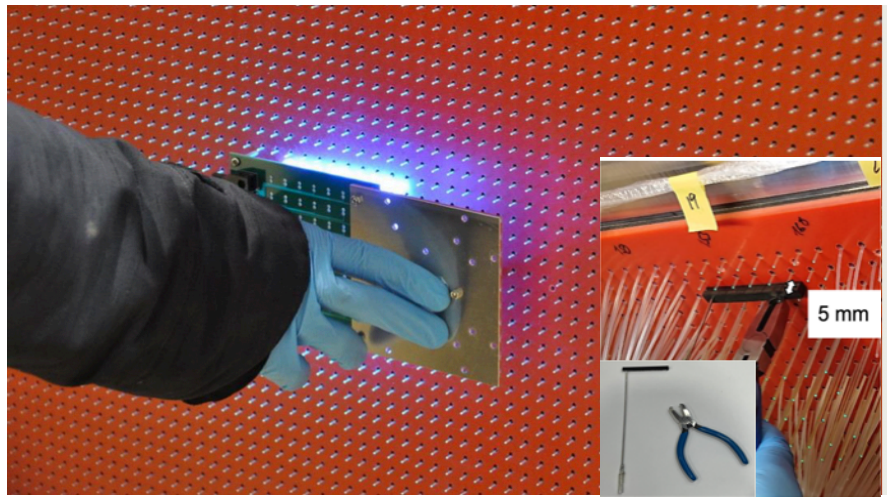


Single 8 × 8 unit of through holes on the upstream panel



MPPC64-PCB

Quality control:
Light yield > 70%



Downstream panel

Vertical fibers:
- **In total**: ~35k fibers (552 PCBs)
- **Broken**: 42 fibers

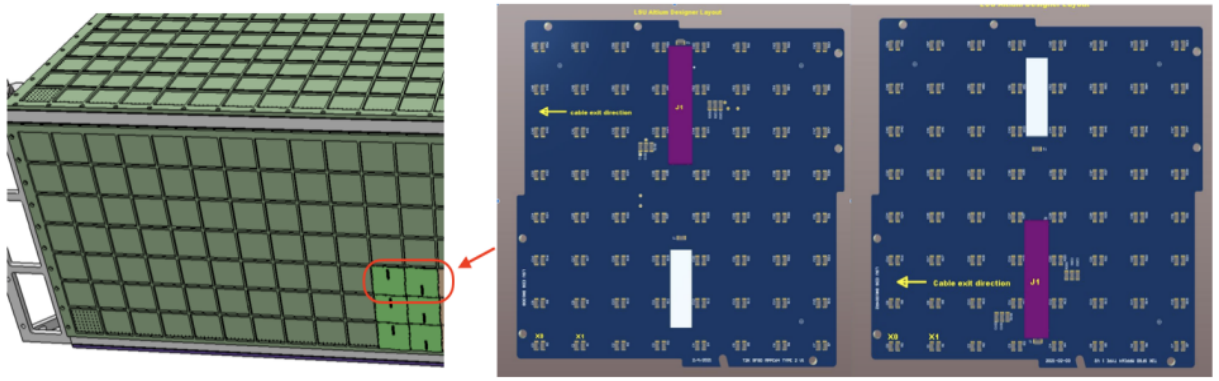
Horizontal fibers:
- **In total**: ~21k fibers (329 PSBs)
- **Broken**: 21 fibers

The broken fibers were replaced

MPPC64 – PCB. MPPC's characteristics

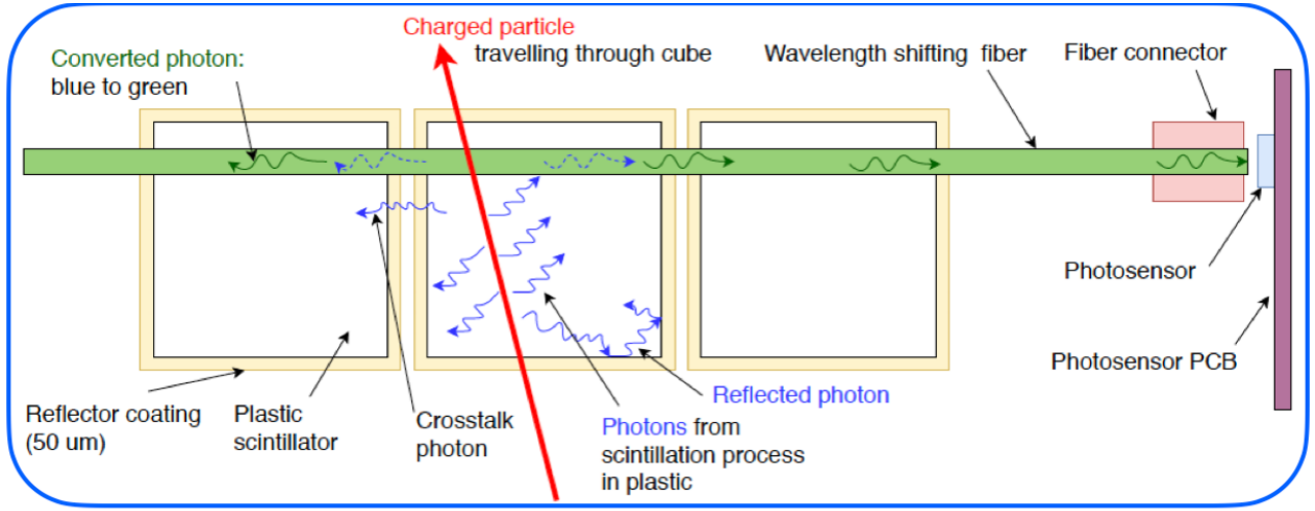
MPPC64-PCB designs for the two connector positions

- 56,384 Multi-Pixel Photon Counters (MPPCs)
- MPPC S13360-1325PE (Hamamatsu Photonics K.K)
- 8 × 8 arrayed MPPCs on a printed circuit board (PCB)
- 881 MPPC-PCBs in SuperFGD in total

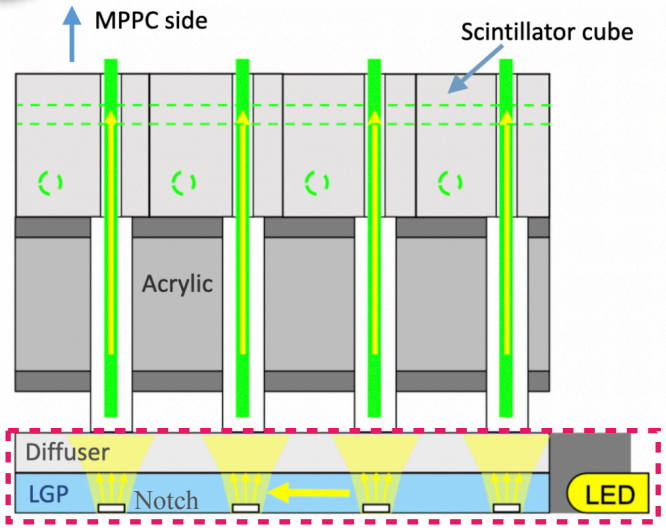


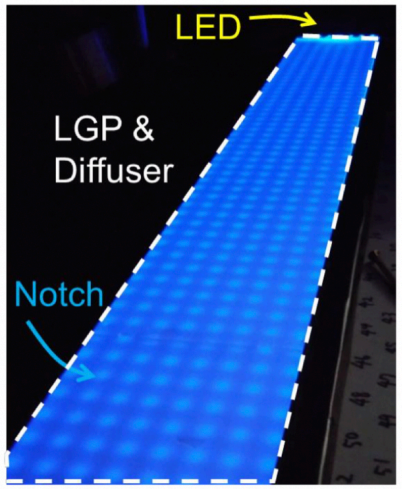
Item	Specification
Pixel pitch (μm)	25
Effective photosensitive area (mm^2)	1.3 x 1.3
Number of pixels	2668 pixels
Package type	Surface mount
Fill factor (%)	47
Breakdown voltage (V)	53 ± 5
Photon detection efficiency (%)	25
Gain	7.0×10^5
Dark noise rate (kHz) at 0.5 p.e.	70
Crosstalk (%)	1

Charged particle interactions with the detector substance (as in the SuperFGD):



SuperFGD calibration system

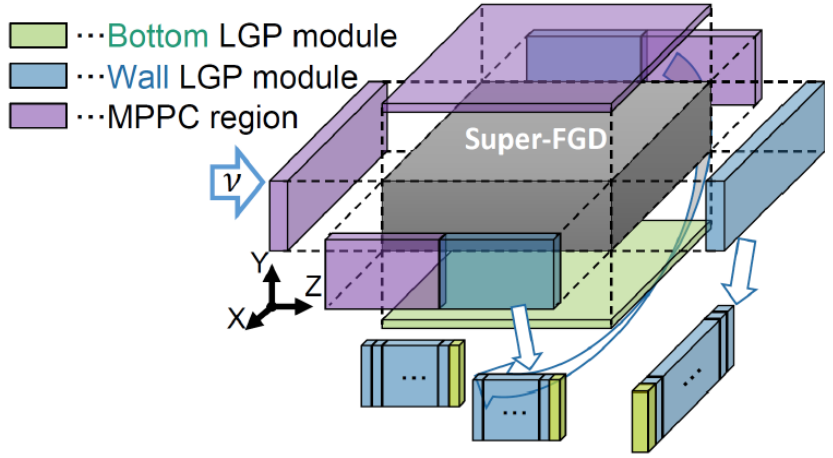


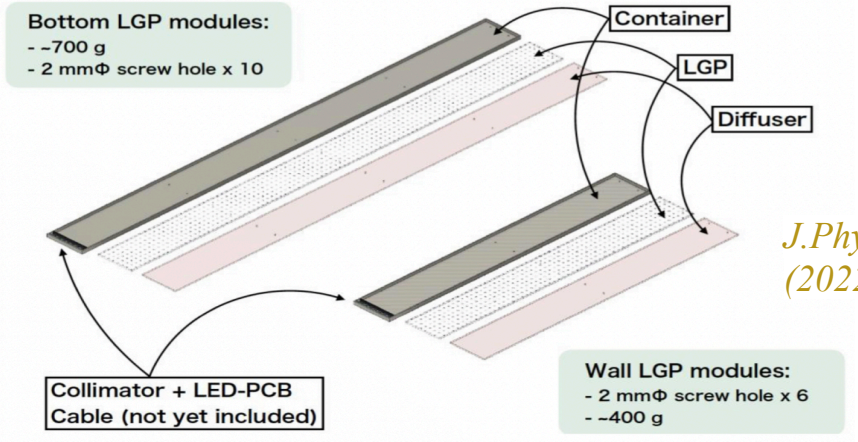


LGP module

Integration design of the LGP modules on the box surface:

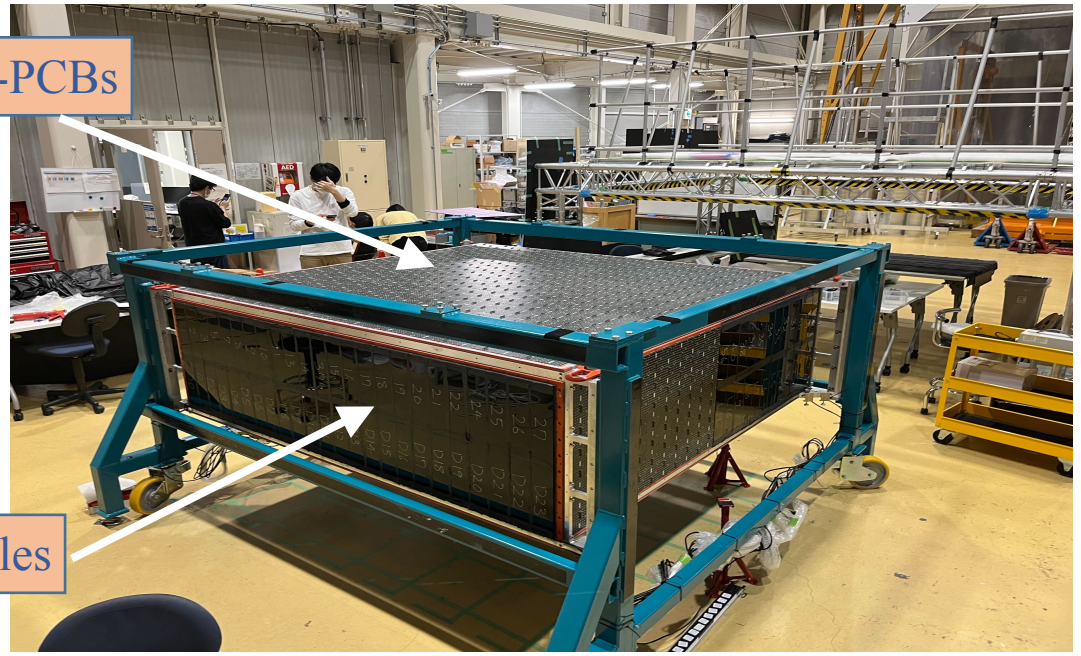
- Bottom LGP module
  - 8 x 96 = 768 Notches
  - 46 modules in total
- Wall LGP module
  - 8 x 56 = 448 Notches
  - 47 modules in total





J.Phys.Conf.Ser. 2374 (2022) 1, 012118

Bottom and wall LGP modules
with a length of about 1 m and 0.6 m, respectively

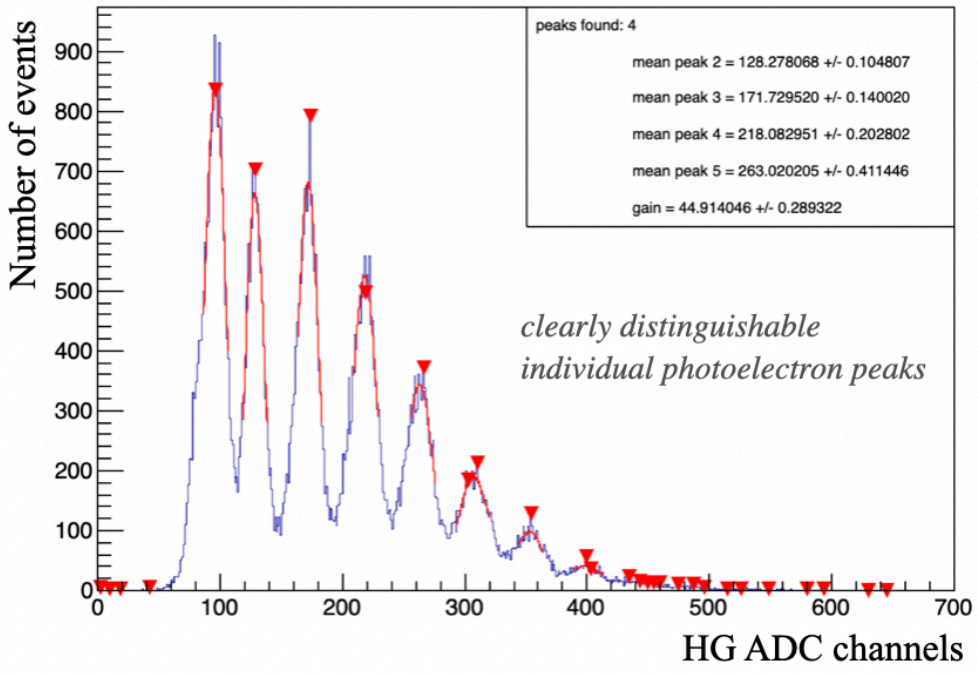


LGP modules and PCBs attachment

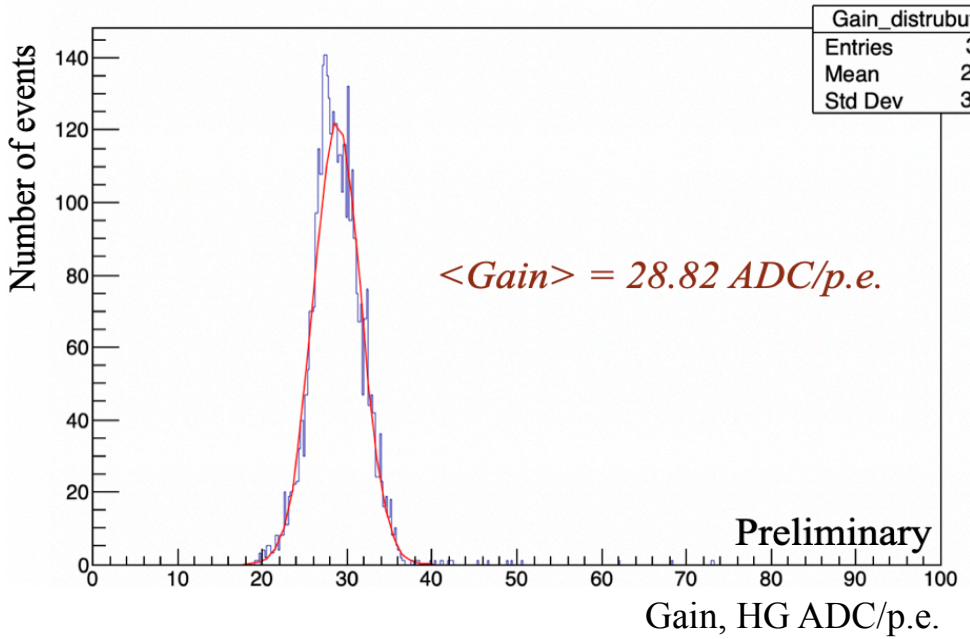
* LGP – Light Guide Plate
LED – Light-Emitting Diode

MPPCs calibration results

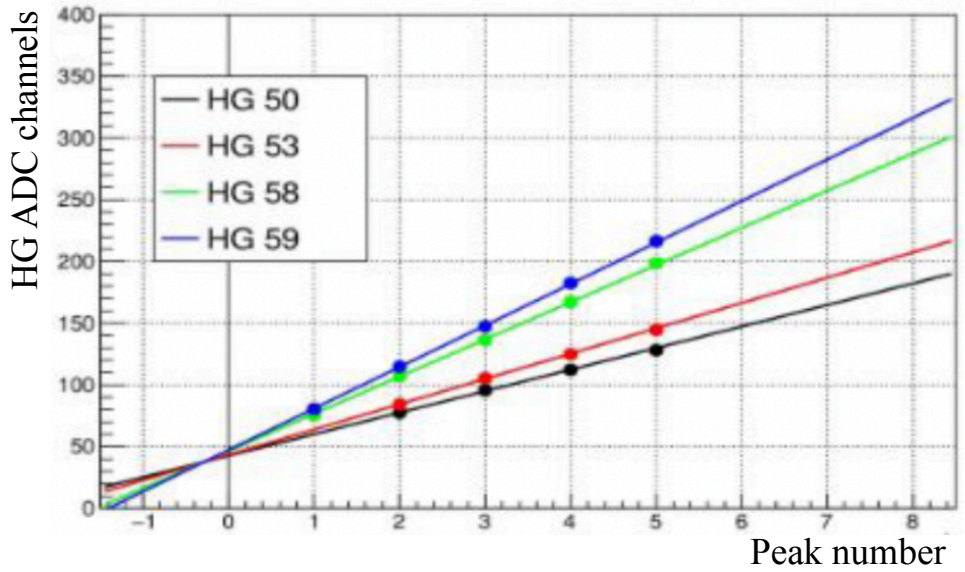
Typical finger plot for a single channel



Gain distribution



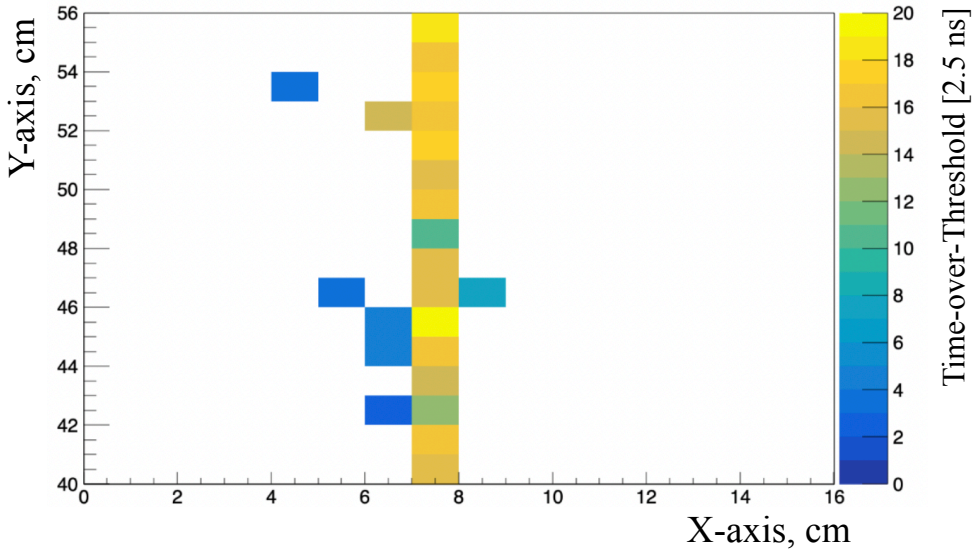
Pedestal finding method for a single channel using different HG values



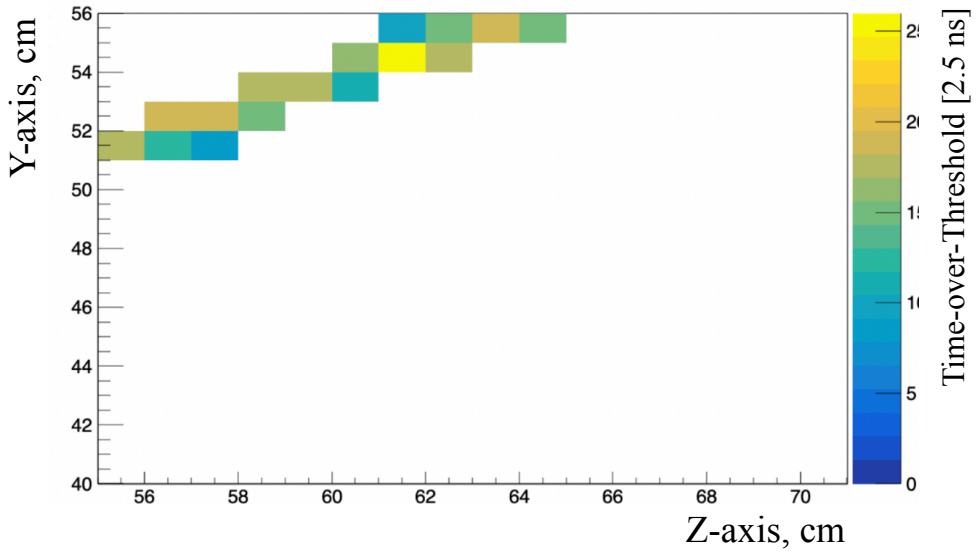
T2K work in Progress

Cosmic events inside the SuperFGD volume

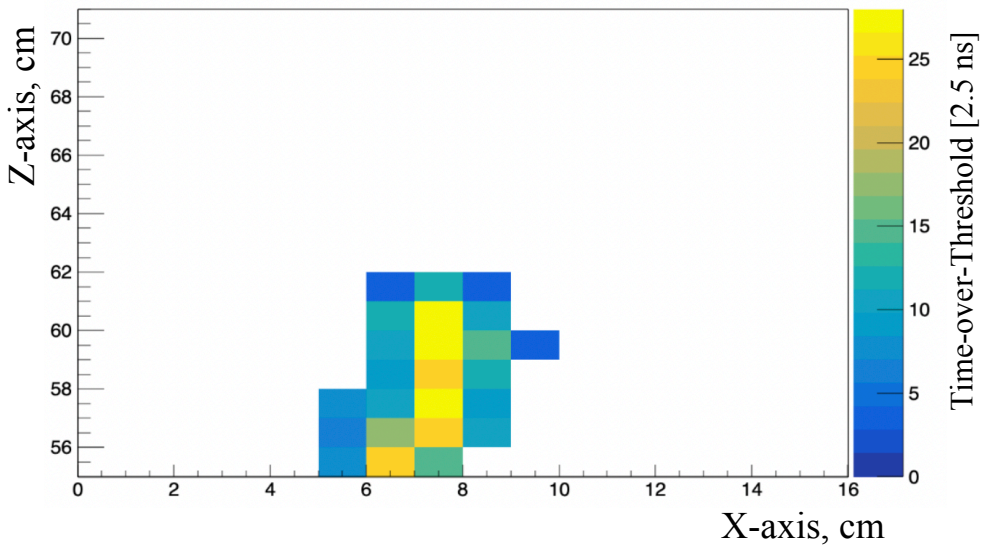
XY-plane



YZ-plane



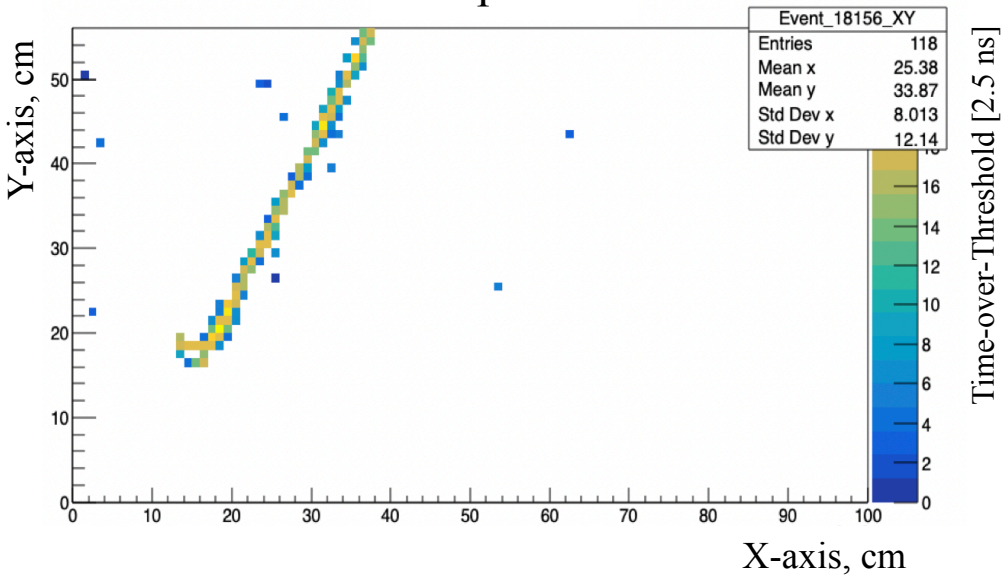
XZ-plane



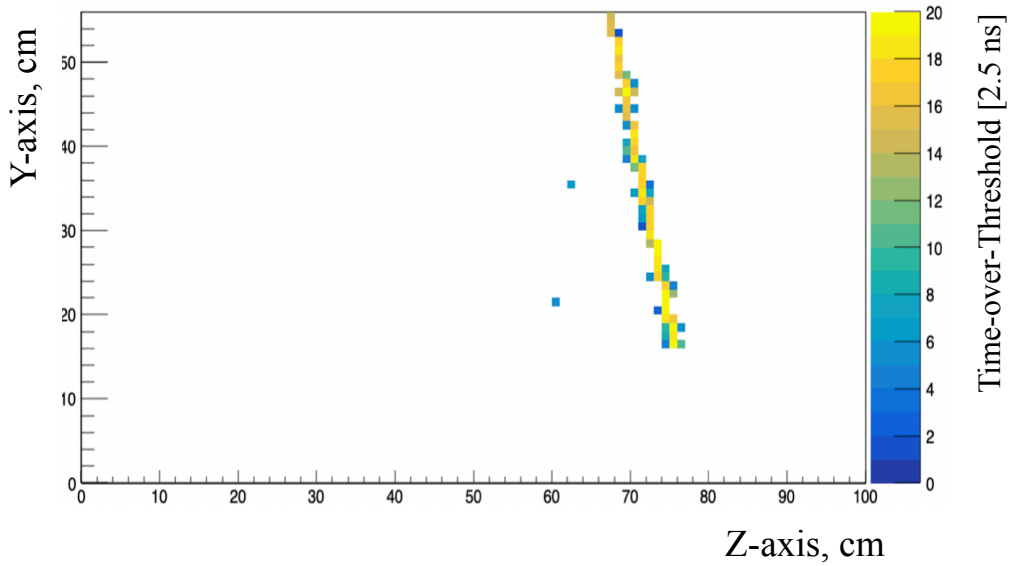
T2K work in Progress

Cosmic events inside the SuperFGD volume

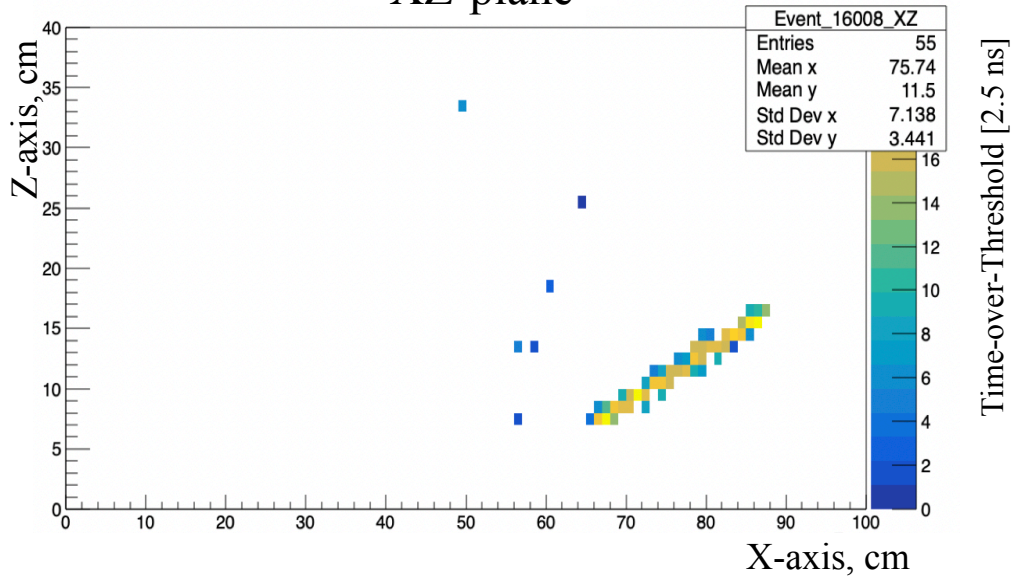
XY-plane



YZ-plane



XZ-plane



3 Crates – 42 FEBs – 10752 channels

T2K work in Progress

Conclusion

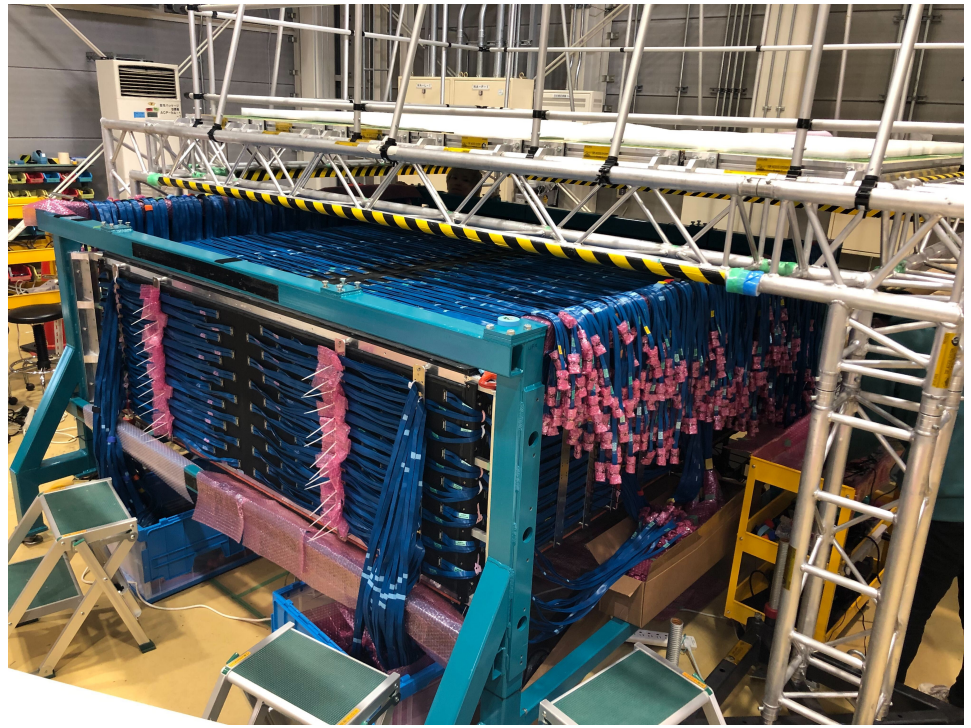
The ND280 Upgrade is aimed at reducing systematic errors in T2K and improving its sensitivity to CP violation phase δ_{CP}

SuperFGD is a central part of the Upgraded ND280 tracker

Upcoming milestones:

- Calibration with cosmics ~ September 2023
- Full electronics readiness ~ October 2023
- SuperFGD installation into the pit ~ October 2023
- Commissioning of the SuperFGD into the pit ~ November 2023
- The first SuperFGD measurement with neutrino beam ~ November 2023

Commissioning of the fully upgraded off-axis ND280 and a set of statistics with neutrino beam is the main task in 2024

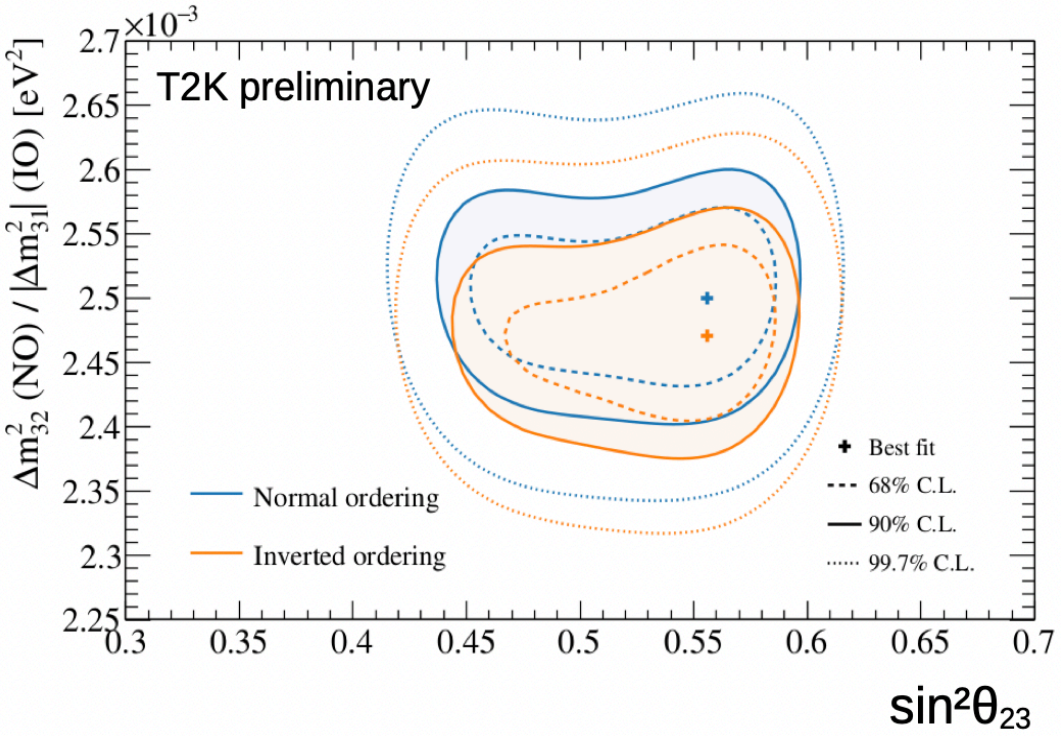


~2 million SuperFGD cubes inside the mechanical box with inserted WLS fibers, LGP calibration system, MPPCs64-PCB, light barrier and cables in the frame of mini Baby-Basket

Backup slides

Latest T2K results

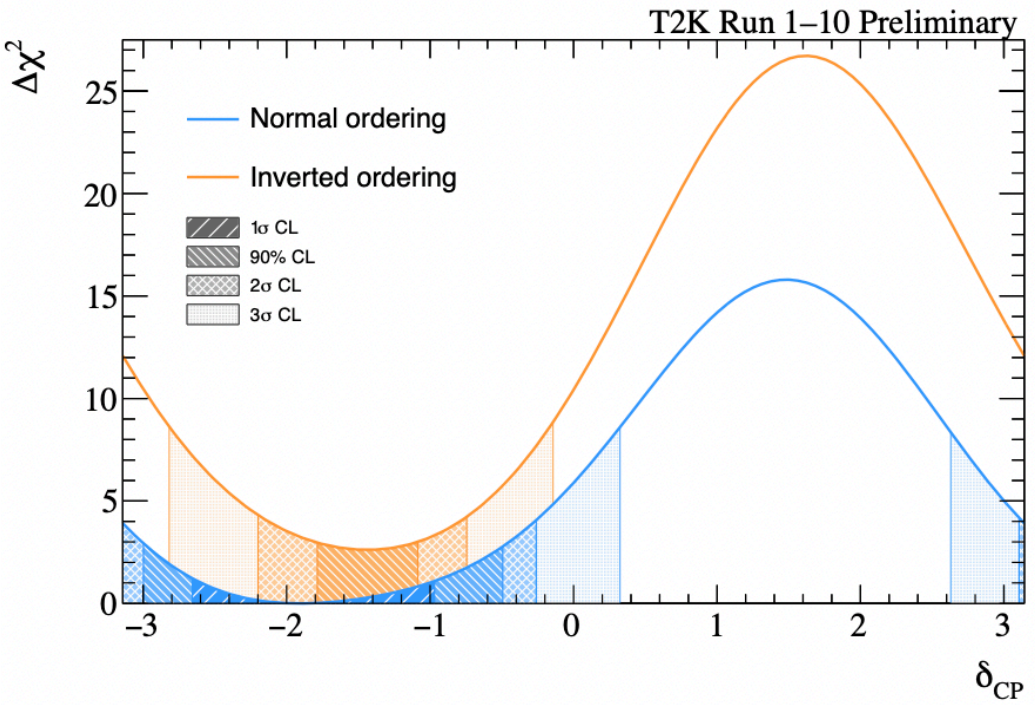
Atmospheric parameters



- Best fit in the upper octant
- Lower octant still allowed at the 68% CL level

Using *θ13* constraint from reactor experiments: $sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

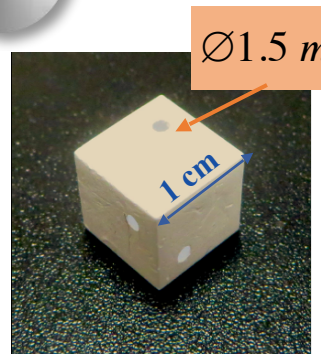
CP violation phase

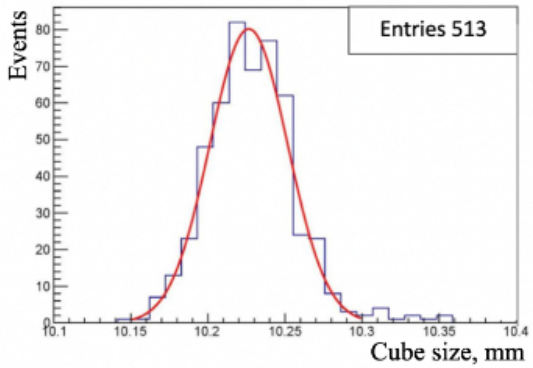


- $\Delta\chi^2$ distribution for δ_{CP} in each mass ordering
- a large region of the δ_{CP} is excluded at 3σ
- CP-conservation ($\delta_{CP} = 0, \pm\pi$) is excluded at 90% CL
- preference for maximal CP violation ($\delta_{CP} = -\pi/2$)

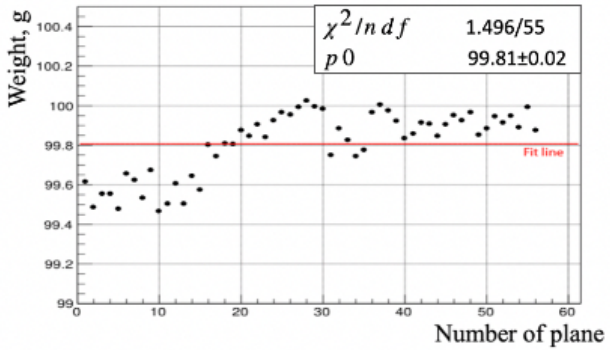
arXiv:2105.06732

Parameters of SFGD cubes

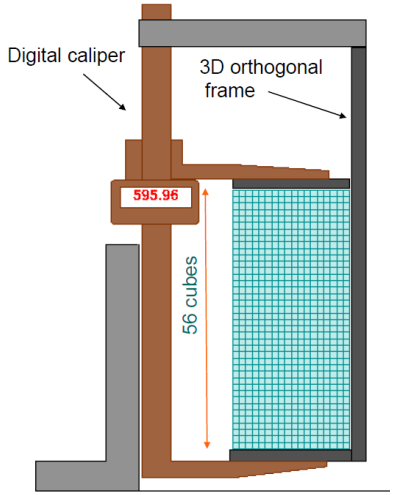




each side (after reflector) = **10.23 mm** +/- σ_x **=0.025 mm**



Weight of a single cube is **0.9977 g +/- 0.0002 g**

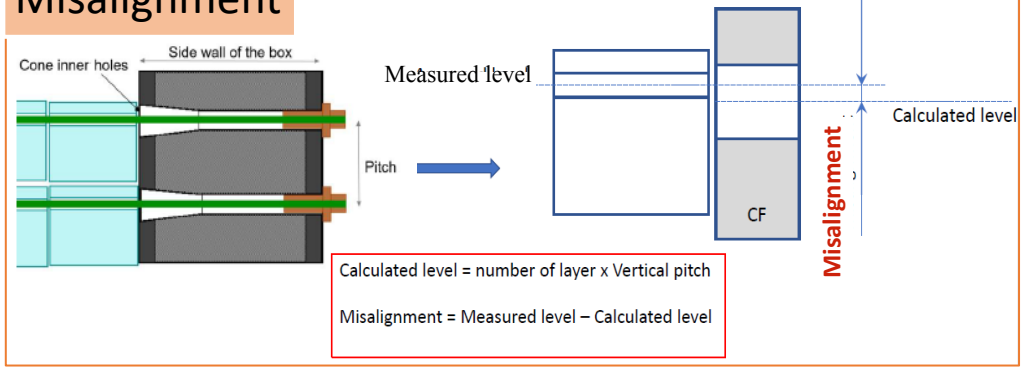


Setup scheme

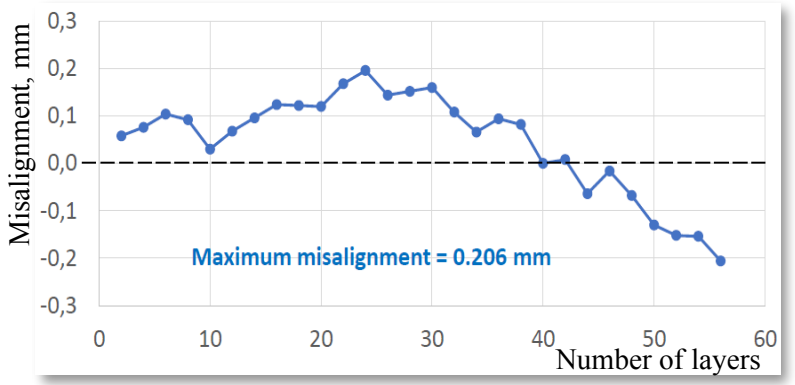
Vertical pitch measurement

56 layers of **18x15** cube pads were assembled with ∅**1 mm** fishing lines in horizontal direction, imitating WLS fibers.

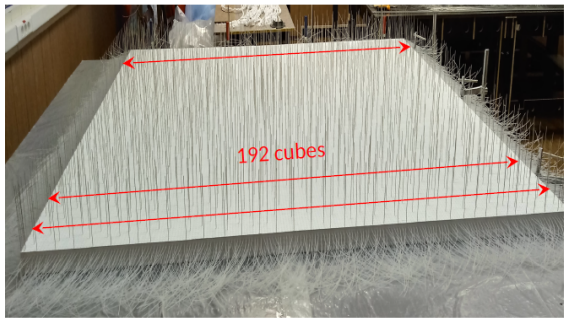
Misalignment



Optimal vertical pitch: 10.281 mm

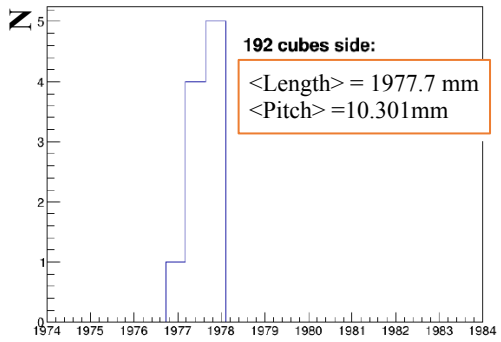


Side length and horizontal pitch

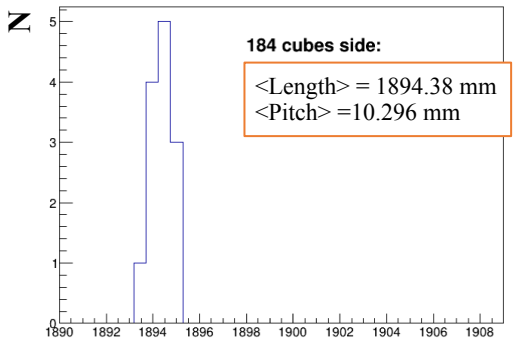


SFGD plane

192 cubes side



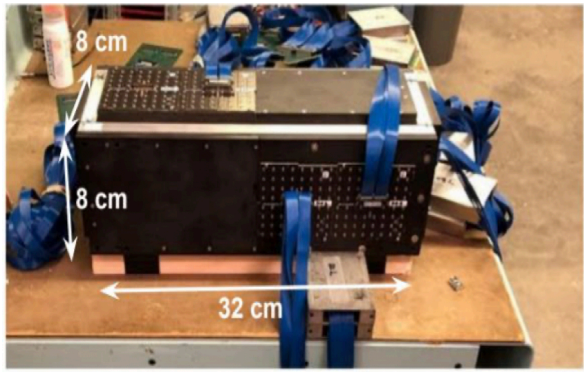
182 cubes side

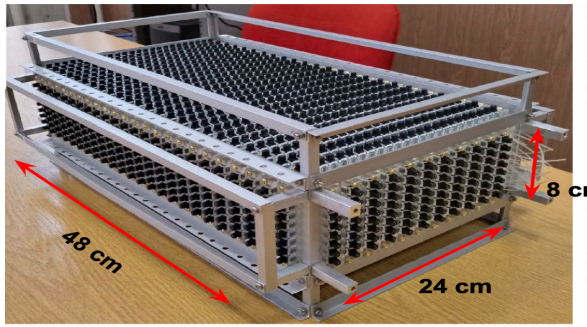


Beam test with neutrons of SFGD prototypes at LANL

Two SFGD prototypes have been tested with neutrons
at Los Alamos National Laboratory (LANL)
Weapons Neutron Research (WNR) facility in both 2019 and 2020.
$E_{neutron}$ = 0 - 800 MeV for two weeks

US-Japan prototype ($8 \times 8 \times 32\ cm^3$)

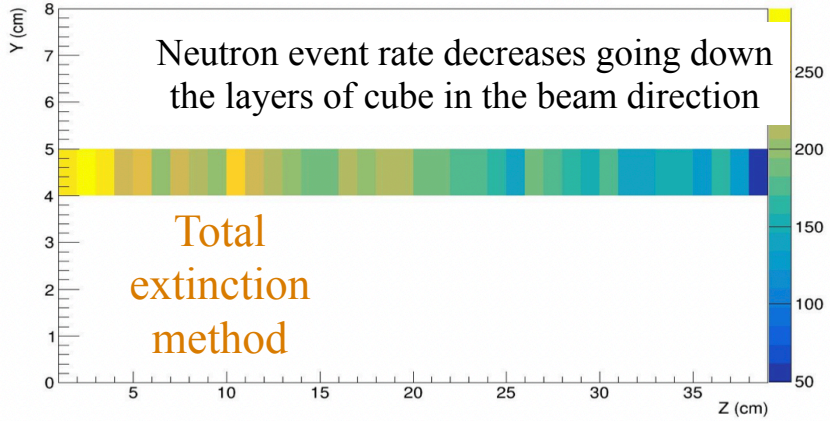




SuperFGD prototype ($24 \times 8 \times 48\ cm^3$)

Neutron beam

Single track events

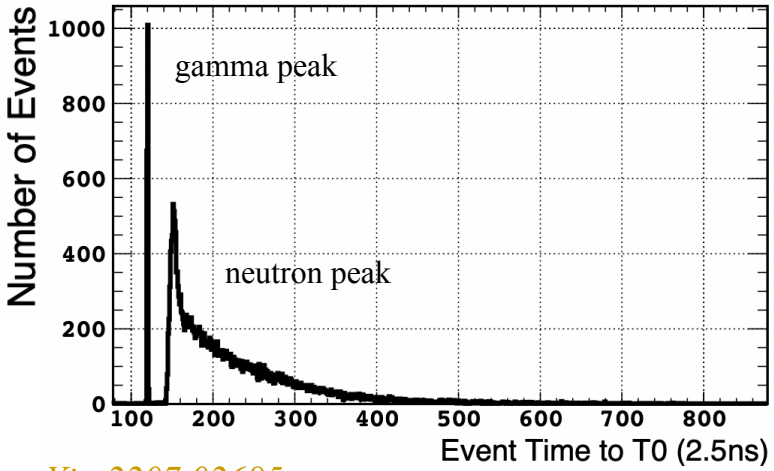


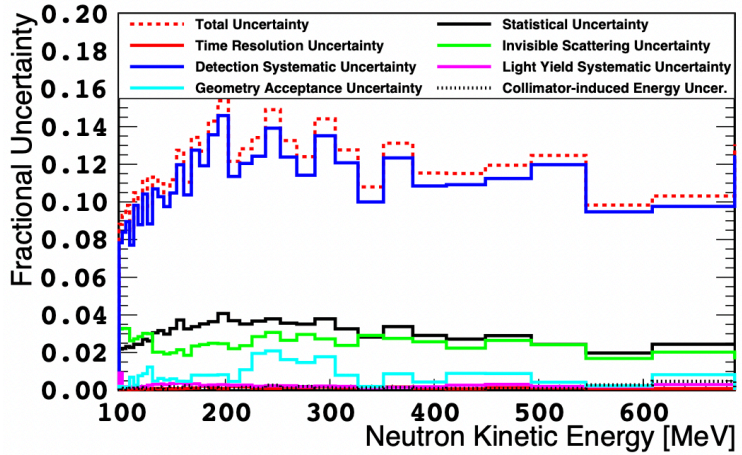
Measurement of event rate $N(z)$ at each layer indicates a total cross section σ_{tot} :

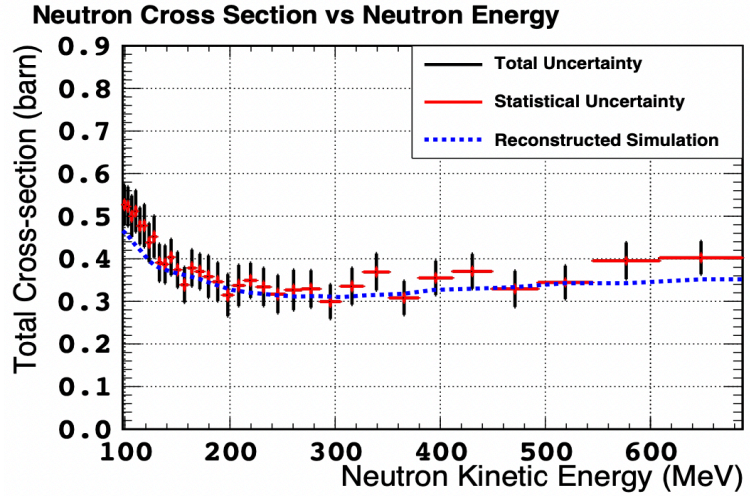
$$N(z) = N_0 e^{-T\sigma_{\mathrm{tot}} z},$$

T - nuclear density
σ_{tot} - neutron total cross section
z - depth along the beam, i.e. layer

ToF spectrum

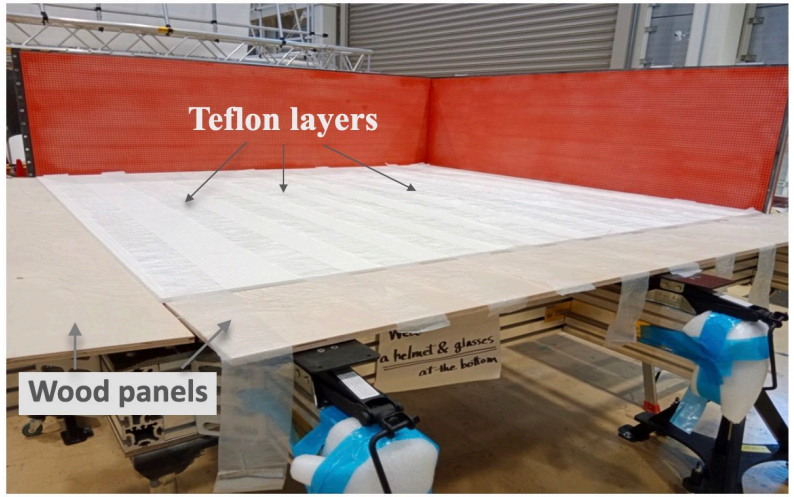




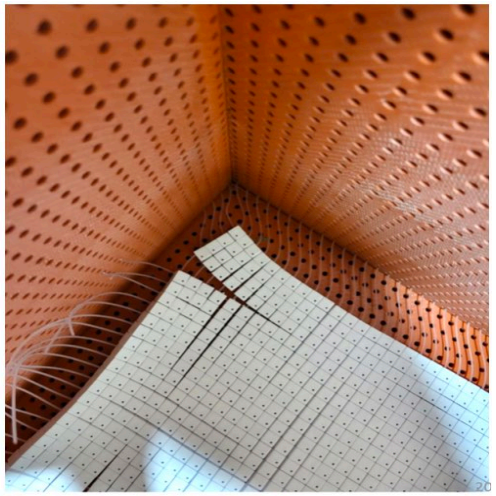


arXiv:2207.02685

SFGD layers assembly

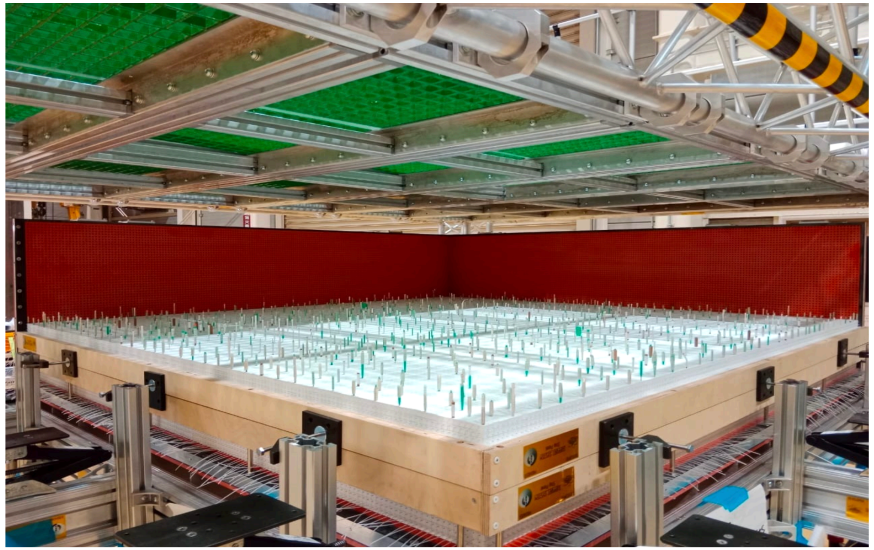


Preparation of teflon lines and two expansion wooden panels



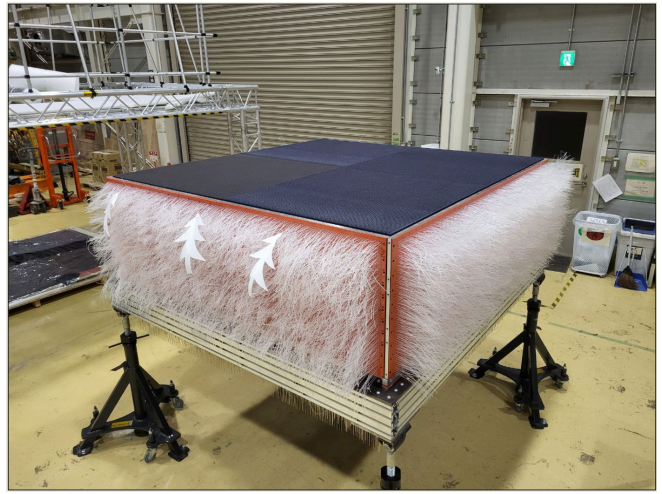
Thread the fishing lines into the holes of the box

Assembly of all 56 layers of SFGD cubes have been completed:

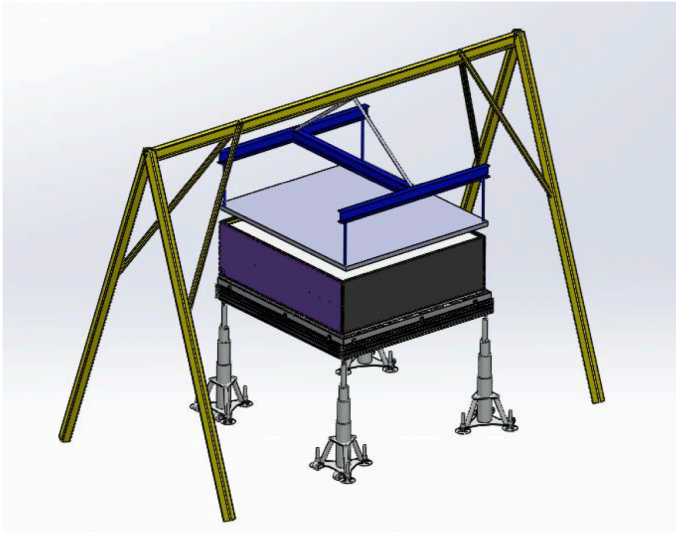


Alignment of the cube holes with steel spokes (~1000, 20 cm, ⌀1.3 mm) and stop panels

Top panel installation

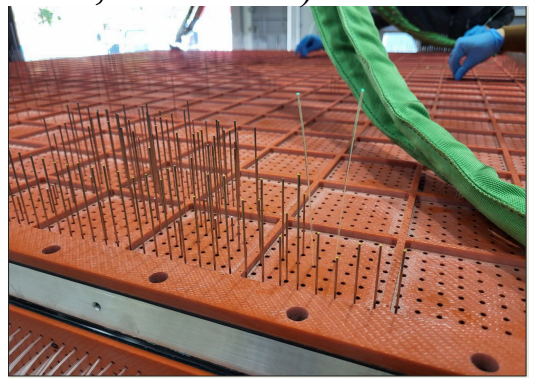


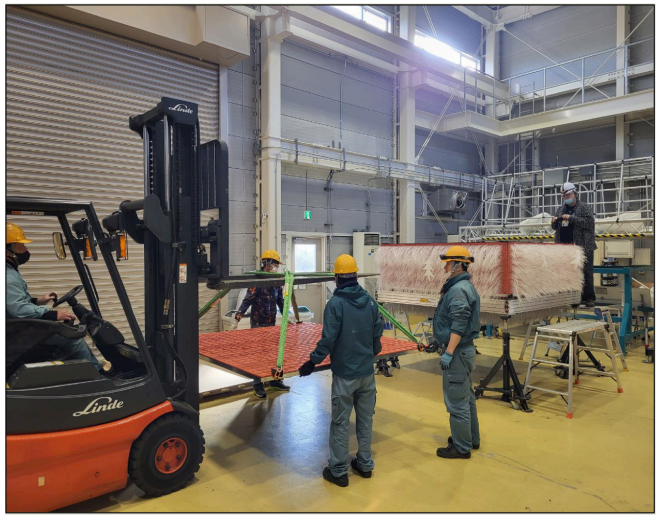
- All welding rods were aligned with the foam level



- Installation scheme

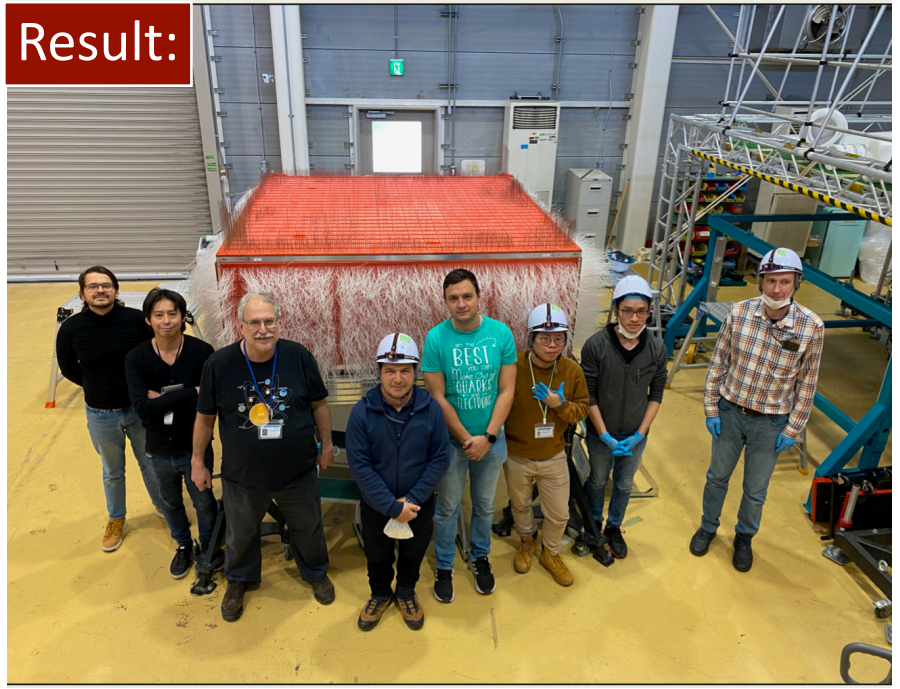
- Alignment of holes after installation (~ 12k, 94 cm, ∅1.2 mm)





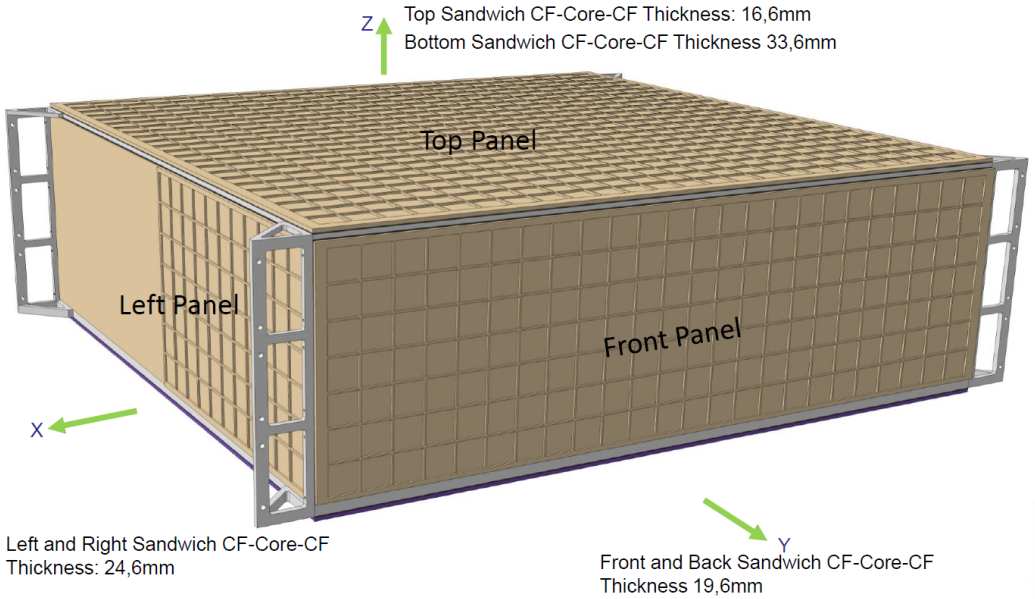
- Installation was carried out by contractors

Result:

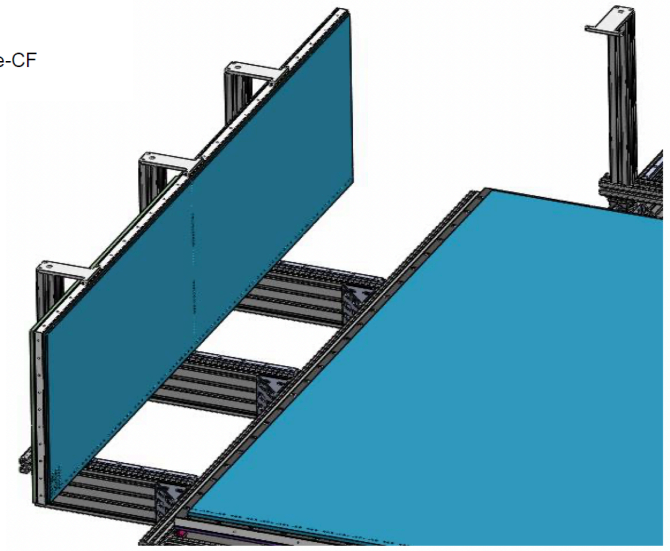


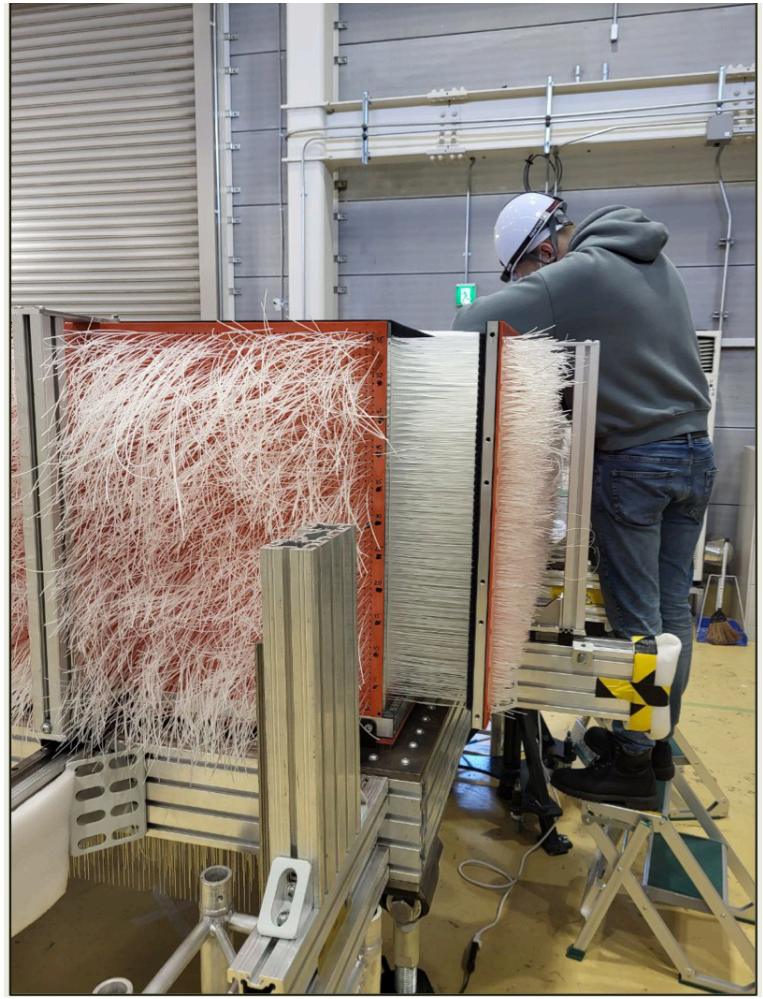
SuperFGD mechanical box. Installing side panels

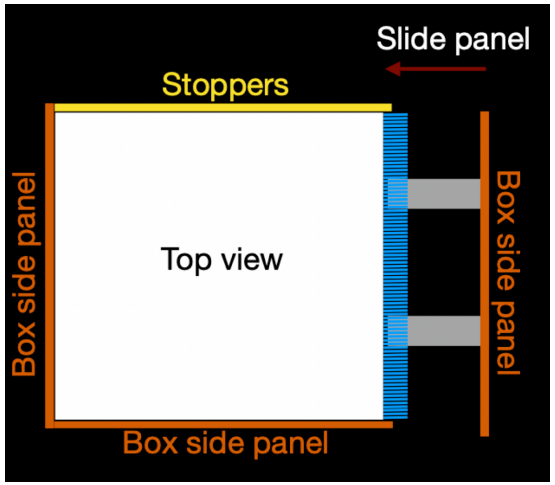
SFGD box structure



Side panel on the movement system



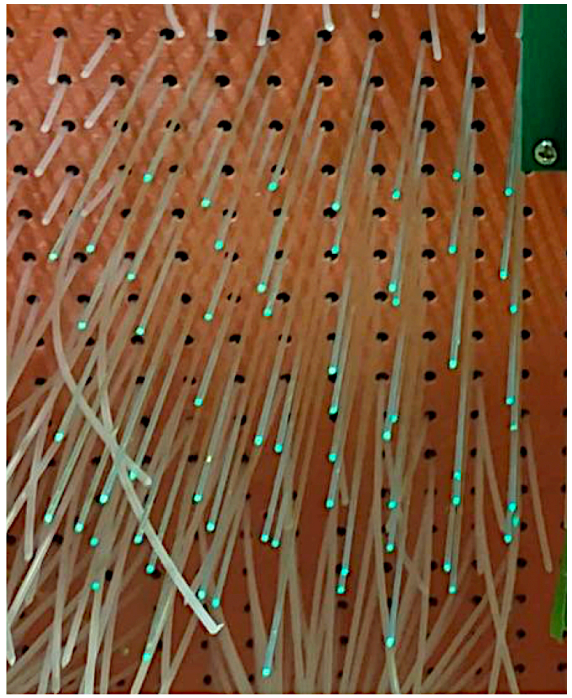




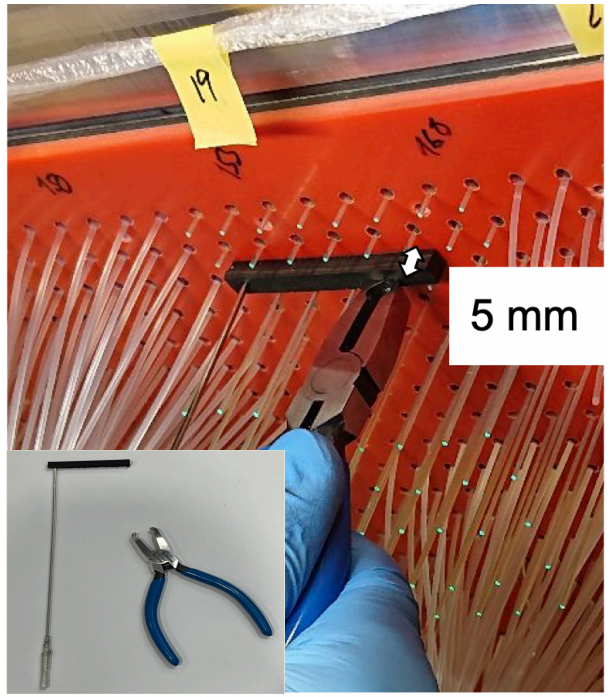
WLS fibers end cutting

Possible problems:

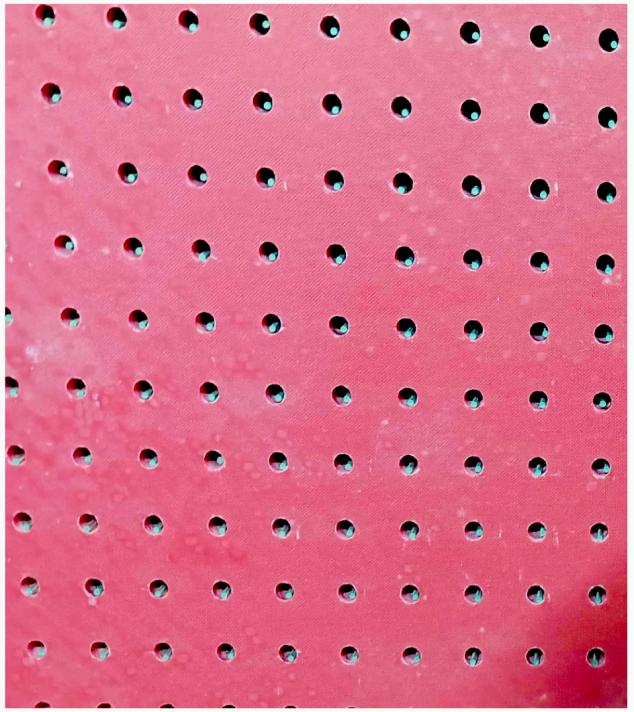
- potential risk to break fibres
- interferes with QC system



Before cutting



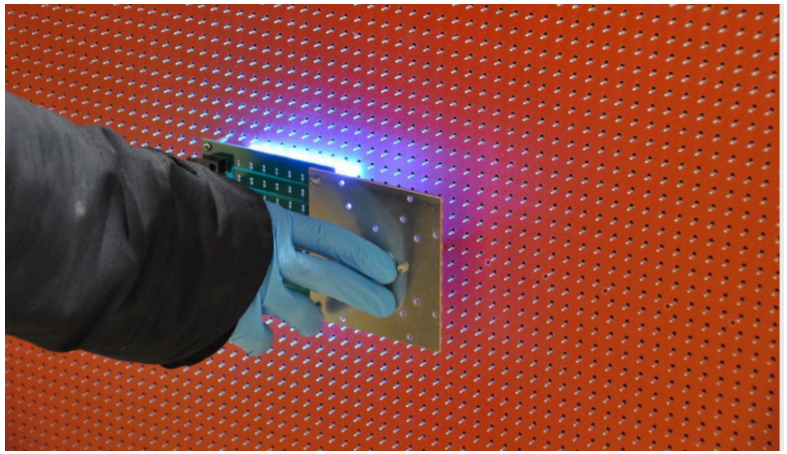
Using nipper a rubber spacer with thickness of 5 mm For QC test



Re-cuttind with 1 mm remaining for LGP modules attachment

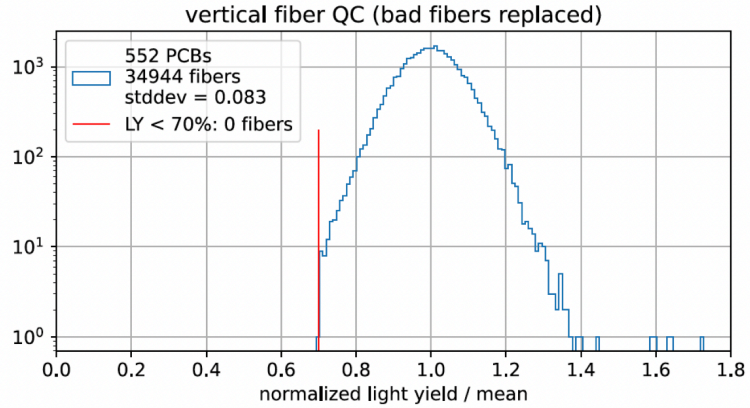
Quality control of the inserted WLS fibers

Quality criterion:
Light yield > 70%

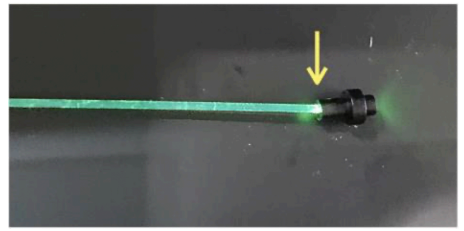


Vertical fibers:
- **In total**: ~35k fibers (552 PCBs)
- **Broken**: 42 fibers

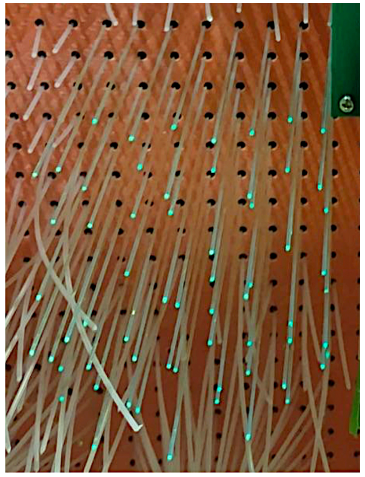
Horizontal fibers:
- **In total**: ~21k fibers (329 PSBs)
- **Broken**: 21 fibers

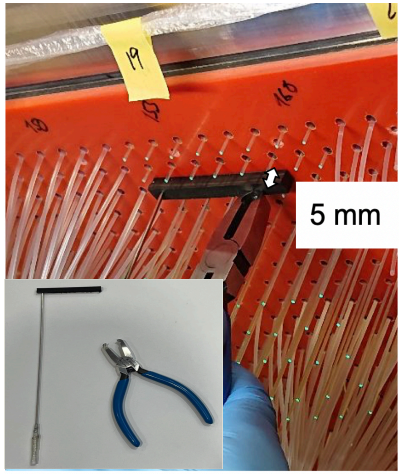


the main cause of fiber damage:



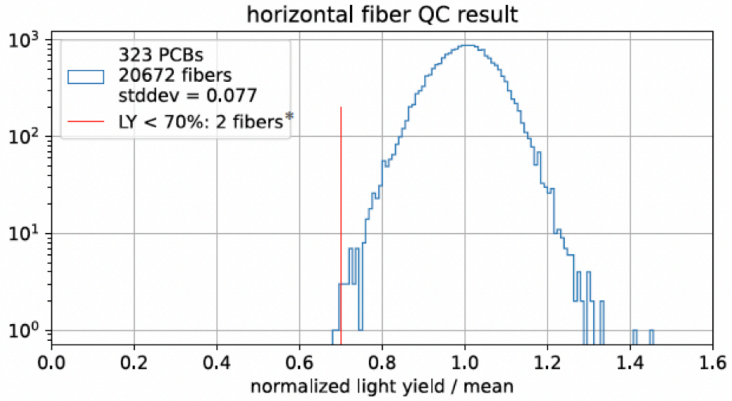
The broken fibers were replaced



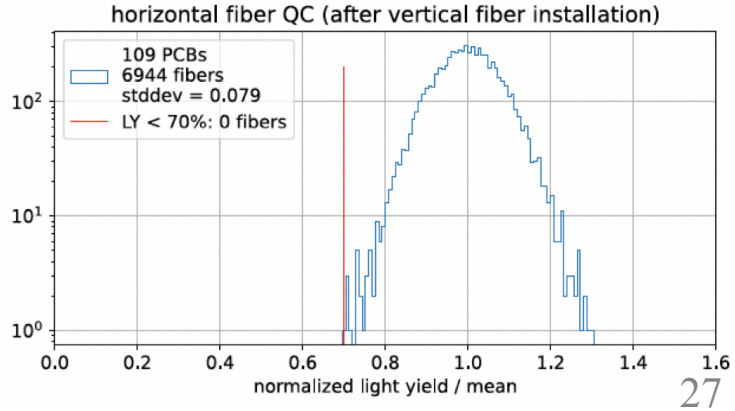


Re-test of horizontal fibres after vertical fibres installation

before vertical fiber installation



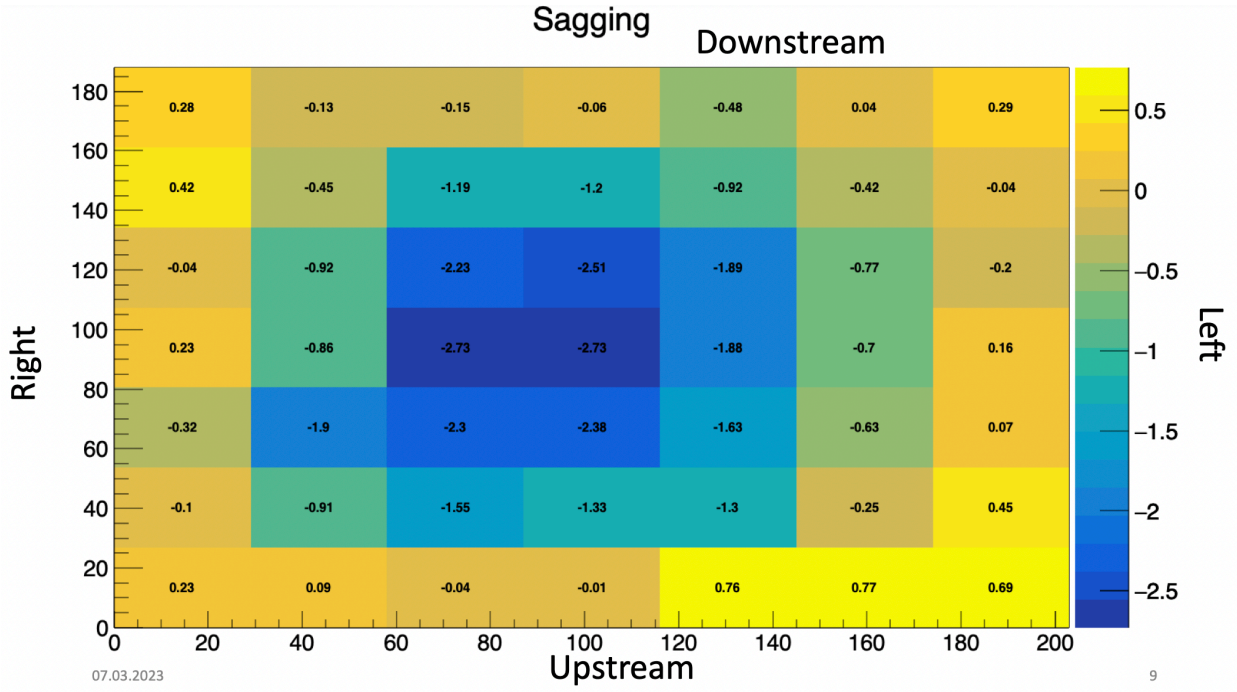
after vertical fiber installation

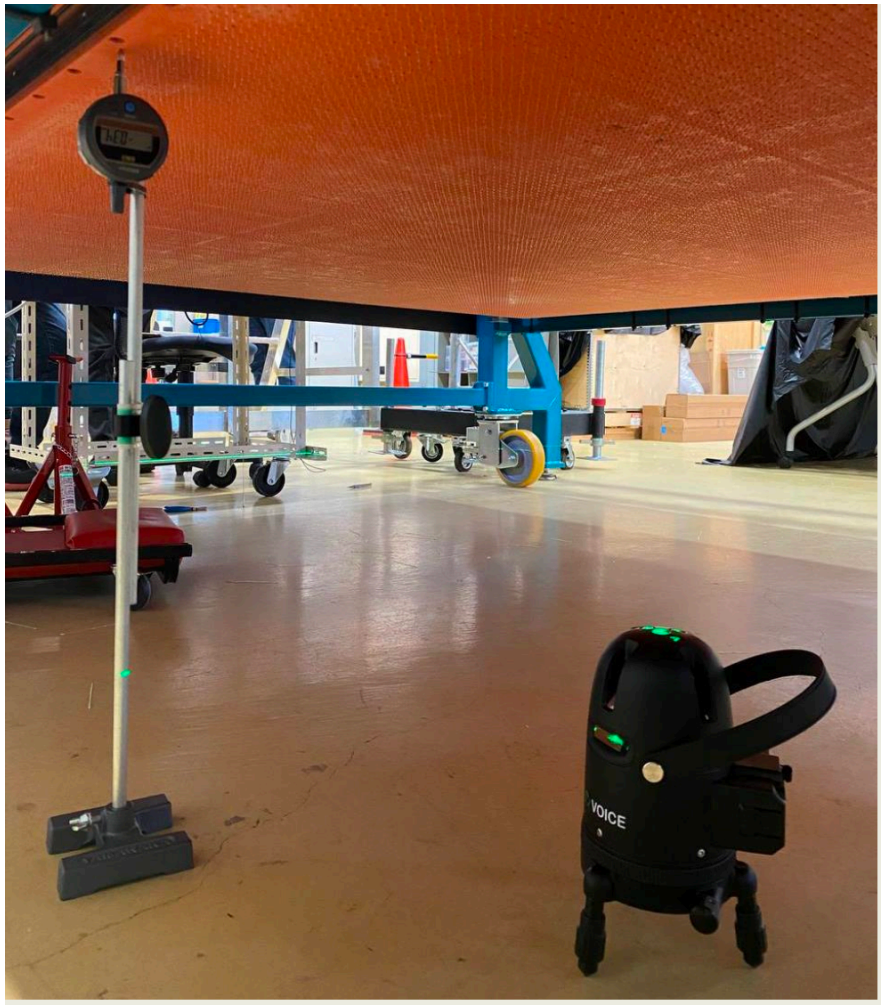


SuperFGD sagging test

Preparation for measurement sagging:

- Grid structure under detector
- Laser level
- Caliper
- Digimatic Indicator (caliper)





Resulting Sag value ~3 mm

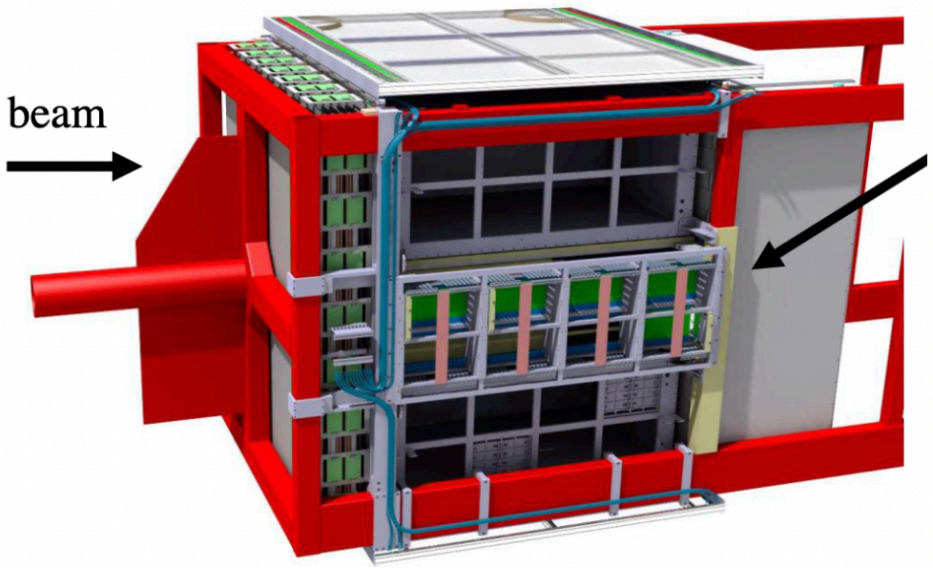
Electronics Overview

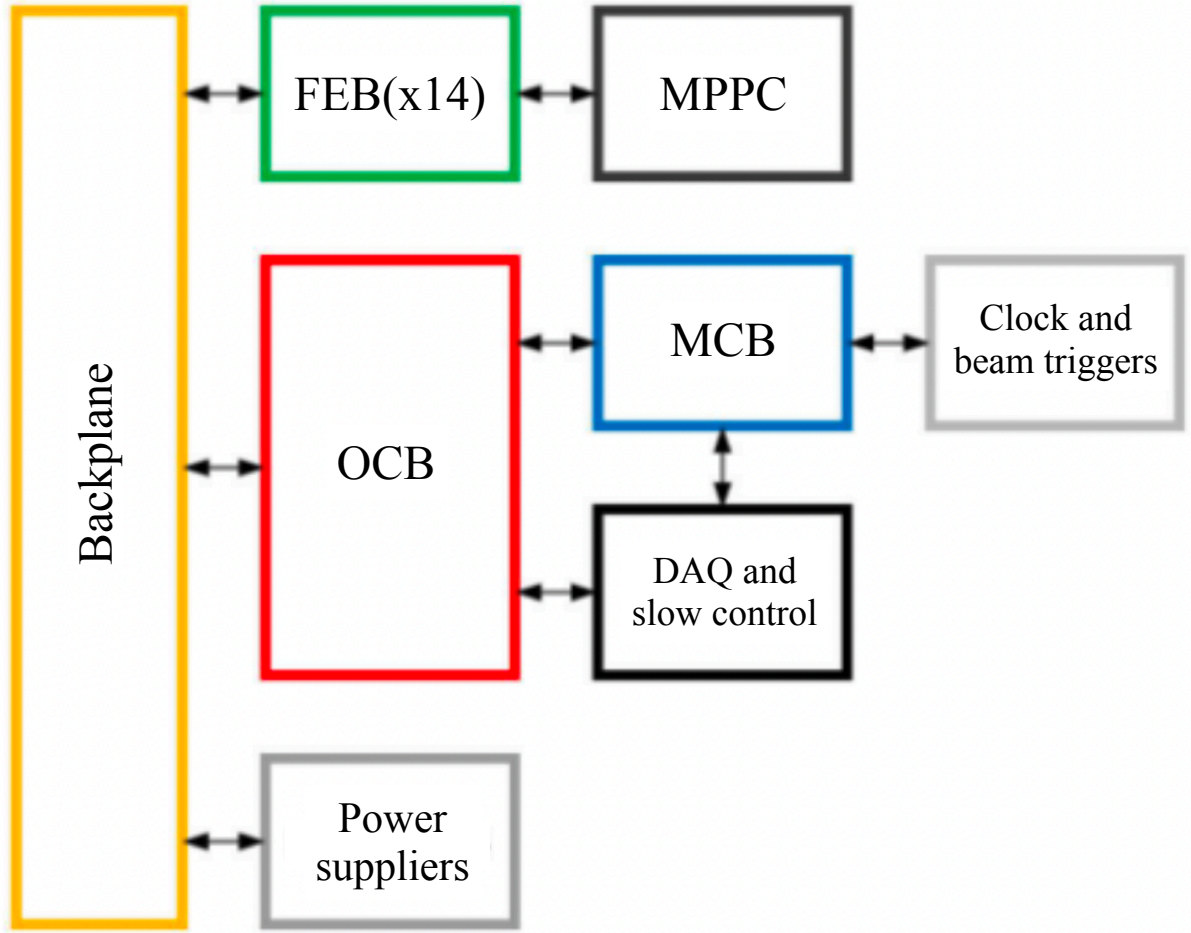
In each electronics crate:

- 14 Front-End Boards (FEBs)
- 1 Optical Concentrator Board (OCB)
- 1Backplane

Outside the crate:

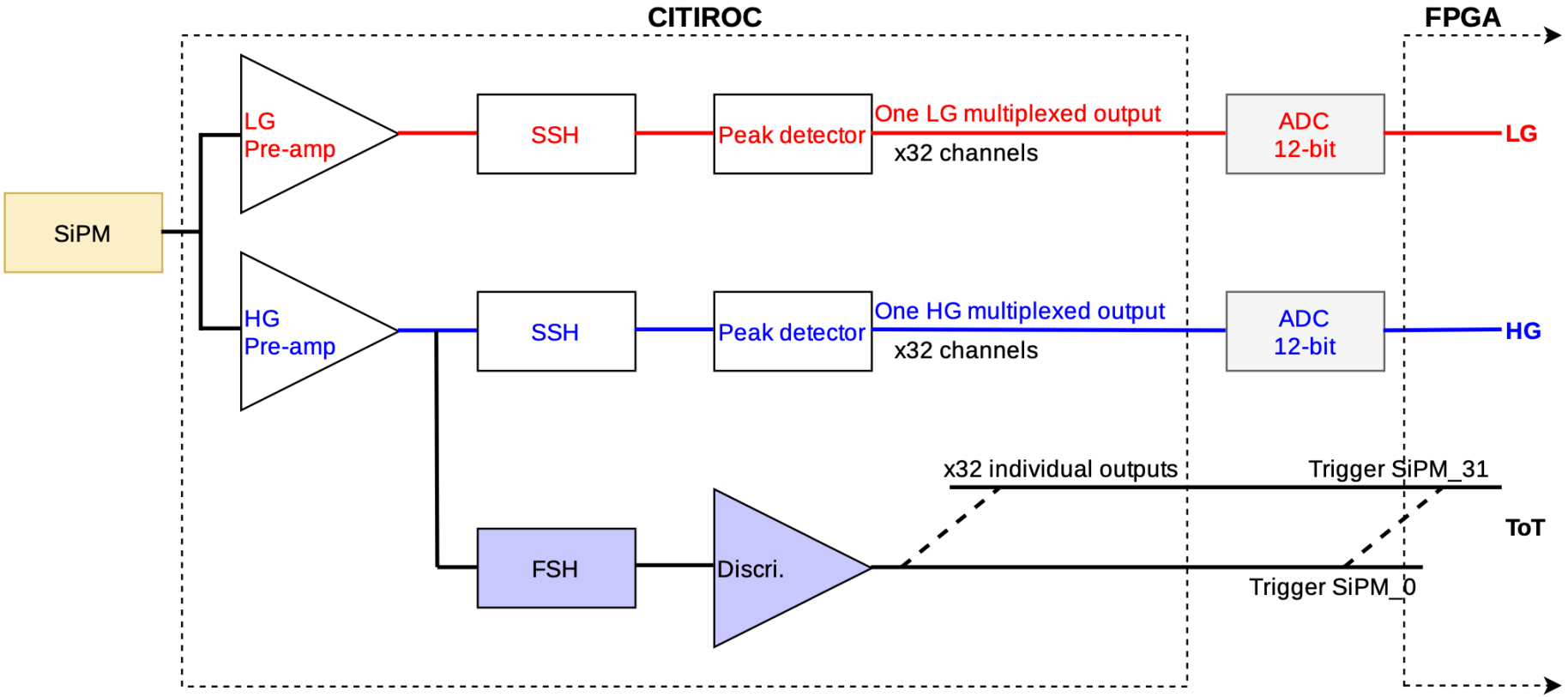
- 1 Master Clock Board (MCB)





Threshold study

Three signal outputs providing amplitude information for an event:



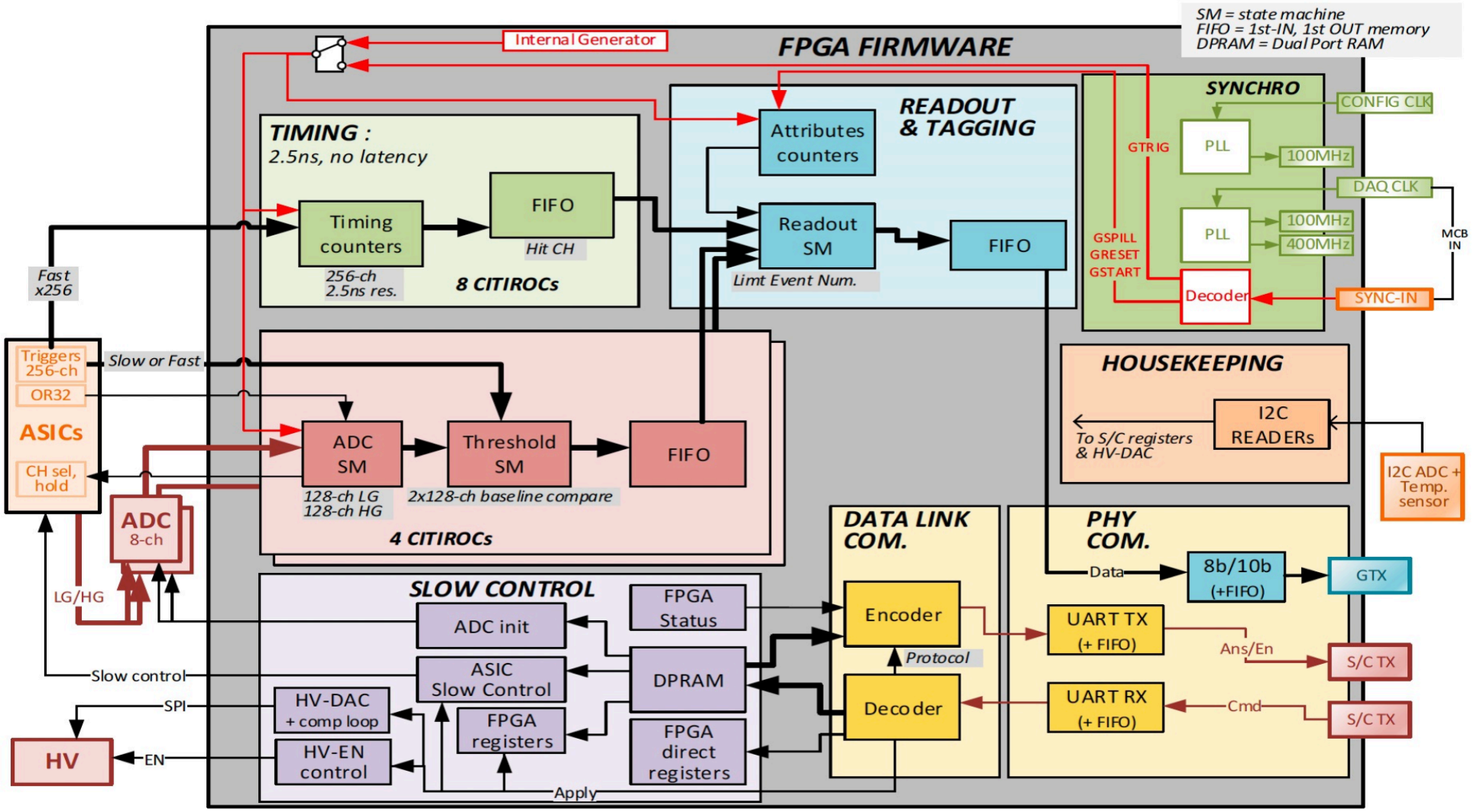
Low Gain

High Gain

Time – over – Threshold

CITIROC (Cherenkov Imaging Telescope Integrated Read Out Chip)
ASIC (Application-Specific Integrated Circuit)Field Programmable Gate Array
FPGA (Field Programmable Gate Array)

SuperFGD electronics



MPPCs calibration results

DAQ setup at J-PARC

- MCB v1
- OCB
- Backplane v1
- 3 FEBs v2
- LED driver
- Oscilloscope
- Kaladin
- MPPCs PCBs