Parameters of a fine-grained scintillator detector prototype with 3D WLS fiber readout for a T2K ND280 neutrino active target

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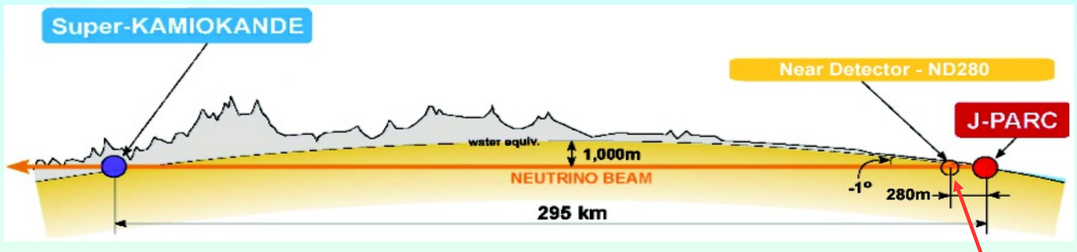
14th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba (Italy), May 27 – June 2, 2018

Highlights

- A small superFGD detector prototype was tested in charge particles beam and at test bench with cosmic rays. 125 scintillator cubes of 1x1x1 cm^3 were assembled in 5x5x5 array. 3D fiber readout was implemented by 1.3 m long Kuraray Y11 WLS fibers and Hamamatsu MPPCs.
- Average light yield in a single cube was over 40 p.e./MIP per a readout fiber.
- Time resolution for a single cube with two readout fibers was σ_t = 640 ps.
  Four cubes with 8 readout fibers produced σ_t = 330 ps.
- Optical crosstalk between the cubes was measured to be ~ 3.4% through a single cube side.

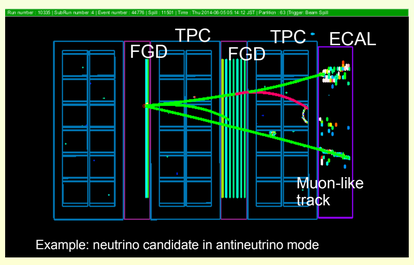
T2K neutrino experiment



The T2K long baseline neutrino experiment has the primary goal to precisely measure neutrino oscillation parameters through measurements of ν_e appearance and ν_μ disappearance from a ν_μ beam. T2K began accumulating the data for physics analysis in January 2010. Discovery and the study of neutrino oscillations resulted in awarding of "Breakthrough Prize for Fundamental Physics" in 2016 to about 1300 scientists from the T2K and other neutrino experiments.

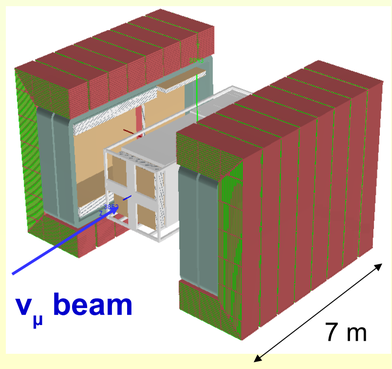
In 2017 the T2K collaboration launched the Near Detector Upgrade project. The upgrade is targeted at reducing systematic errors in T2K's search for CP violation in the neutrino sector.

ND280 is a set of tracking sub-detectors installed inside UA1 magnet.



Example: neutrino candidate in antineutrino mode

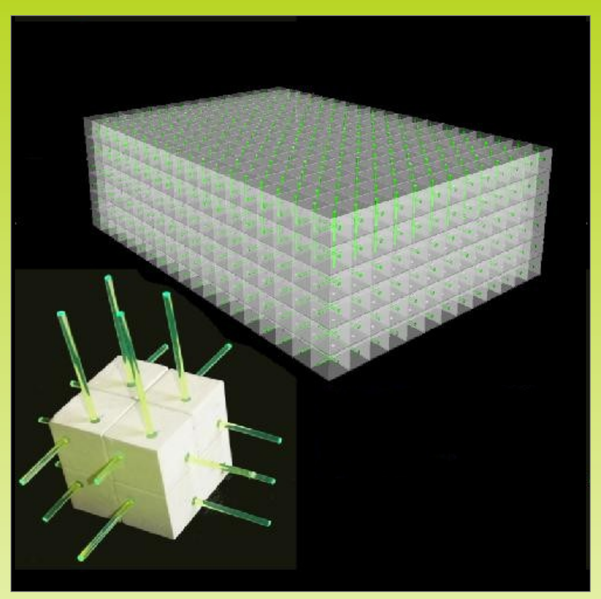
ND280 scintillator detectors (FGD) were designed as arrays of bars located perpendicular to the beam axis. Geometry is optimized to detect particles propagating in the forward direction that resulted in direction-dependence of acceptance and resolution for neutrino events.



To reach more isotropic response the new scintillator detector with 3D fiber readout is proposed as the neutrino target: SuperFGD (fine-grained detector)

SuperFGD concept with 3D fiber readout

SuperFGD will be installed upstream of the beam between two TPCs (time-projection chambers) in addition to the existing FGD detectors. The size is limited by available space inside the UA1 magnet.



Detector size: 0.6 x 1.8 x 2.0 m^3

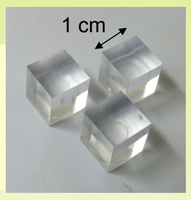
Granularity: 1x1x1 cm^3 cubes

Number of cubes: 2,160,000

Number of readout channels: 58,800

Readout : Y11 Kuraray WLS fibers of 1 mm diameter viewed at a single end with surface mount Hamamatsu MPPCs.

Array of 8 scintillator cubes illustrates the readout method. A single WLS fiber is going through a raw of cubes. One end of the fiber is viewed by a photosensor, another end is covered by a reflector. Each cube is viewed by 3 orthogonal fibers.



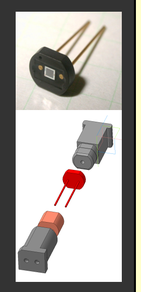
Cubes: made by injection molding from polystyrene with PTP+POPOP dopants, then covered by a chemical diffuse reflector (by etching the surface in a chemical solution) of ~50 μm thickness. Cube size tolerance is specified ± 20 μm. Three orthogonal holes of 1.5 mm diameter are drilled through each side.

WLS fibers: 1 mm dia. double-clad Kuraray Y11 (S-type), emission peak ~500 nm, decay time ~12 ns, maximum length is over 2 m. Open end of the fiber is planned to cover with a reflective paint.

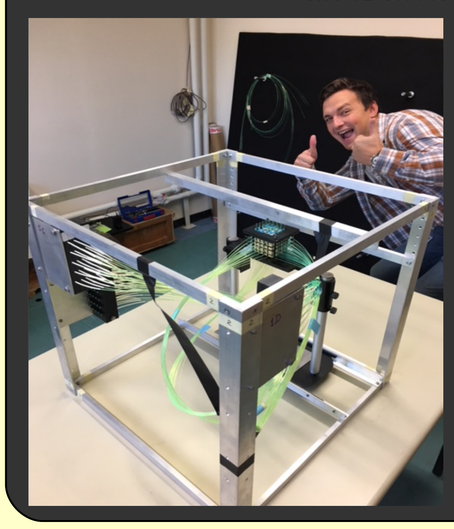
MPPC: surface-mount type S13360-1325PE, sensitive area 1.3x1.3 mm^2, number of pixels 2668, pixel size 25 μm, dark rate 70 kHz (typical), PDE=25% at 500 nm

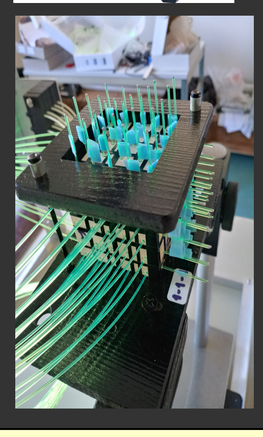
Test of 5x5x5 array at 6 GeV/c beam in CERN

Prototype of 125 cubes with 75 fibers was tested in the charge particles beam. The readout was implemented with 1.3 m long Kuraray Y11 WLS fibers and Hamamatsu MPPCs S12571-025C. MPPC sensitive area is 1x1 mm^2, number of pixels is 1600. Open end of the fiber was covered by aluminized reflective paint Silvershine.
Beam spot was localized by two small trigger counters of 3x3x10 mm^3 size. The counters were placed in front and back of the prototype.

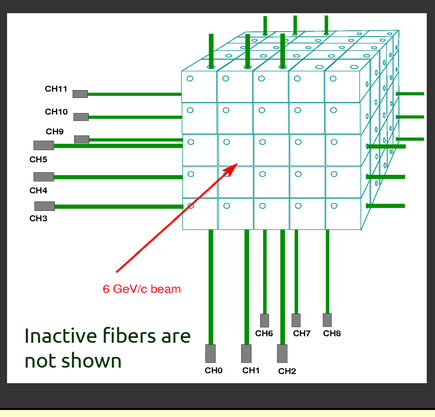


Two types of front-end electronics were used sequentially:
1) multi-channel boards developed on CITIROC ASICs for the Baby MIND spectrometer ; 2) 16-ch. CAEN digitizer DT5742 with 5 GHz sampling rate and 12-bit resolution.

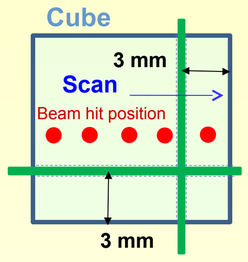




The multi-channels boards do not provide good time resolution, so all results reported are refered to the digitizer which read out 12 fibers.



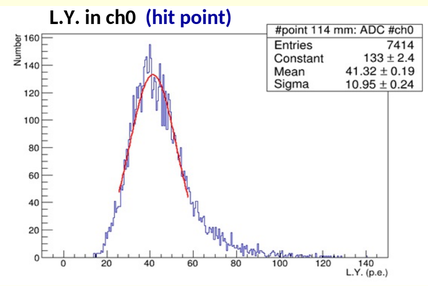
Beam test results for light yield and timing

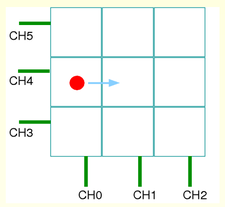


Beam scan with step of 2 mm was done across a few cubes in horizontal direction. Beam spot is limited by the trigger counters size, **i.e. 3x3 mm^2**.

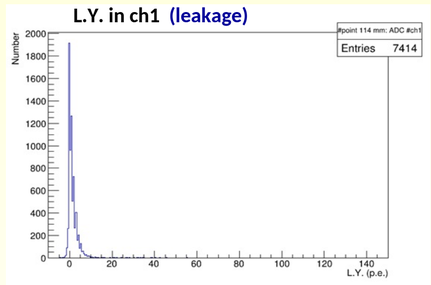
- Light yield: 38-48 p.e. per a single fiber *(depends mainly on the MPPCs).*
- Typical light yield: ~42 p.e. per a single fiber.
- Typical light yield: ~80 p.e. per two fibers through a cube.
- Average time resolution per a single fiber: σ_t= 0.92 ns
- Average time resolution for two fibers (per a cube): σ_t= 0.68 ns

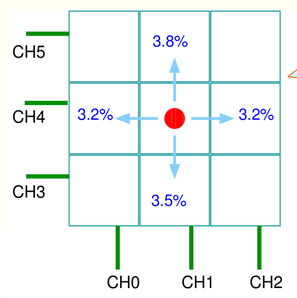
Beam test results for optical crosstalk between the cubes



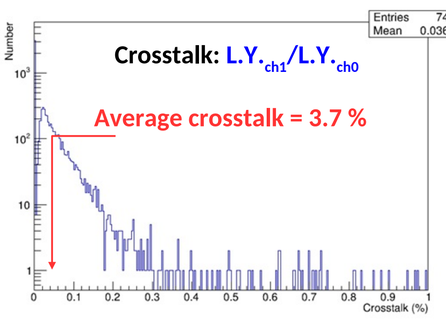


Beam hits cube 0-4. Light leaks in cube 1-4. Crosstalk is the ratio L.Y.$_{ch1}$/L.Y.$_{ch0}$



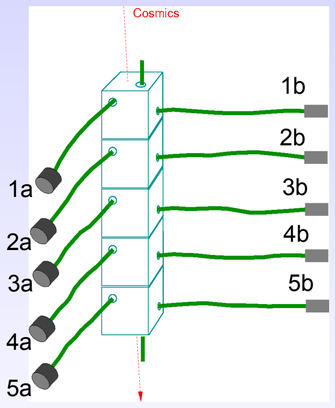


Crosstalk from central cube 1-4 through 4 sides is 13.7% total on event-by-event basis.



Timing for a column of 5 cubes measured with cosmic rays

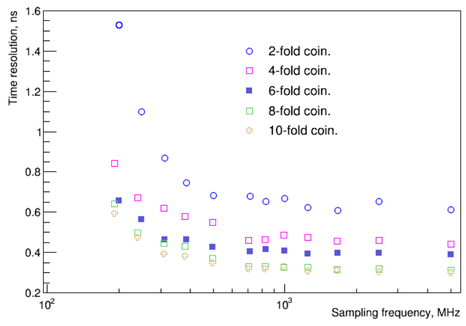
Column of 5 cubes was read out within 5x5x5 cube assembly. Each cube is viewed with two WLS fibers, and one dumb fiber is going through all the cubes. The event was selected if both fibers in upper and bottom cubes have L.Y. > 12 p.e. , i.e. coincidence on four fibers (1a*1b*5a*5b). Average L.Y. per a fiber was 42.5 p.e.



Constant fraction method (fraction 0.1) was used to calculate timing.

Number of cubes	σ_t, ps
1	640
2	480
3	390
4	330
5	310

For a single cube σ_t is an average value for all 5 cubes. The resolution for a single cube is calculated on event-to-event basis as $t_n=(ta+tb)/2$, where *ta, tb* are the times for the fibers *a* and *b*.
The σ_t for n cubes : t = (t1 + t2 +...tn)/n



Time resolution σ_t vs sampling rate of the digitizer.

2-fold coin. : 2 fibers (a single cube)
4-fold coin. : 4 fibers (two cubes)
6-fold coin. : 6 fibers (three cubes)...

Resolution degrades at sampling rate below 500 MHz

References:

1. A. Blondel et al., JINST 13 (2018) P02006 [arXiv:1707.01785]

Larger prototype made of 9200 cubes is being assembled for beam tests in CERN.