Beam test results of 3D fine-grained scintillator detector prototype for a T2K ND280 neutrino active target

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Abstract

An upgrade of the long baseline neutrino experiment T2K near detector ND280 is currently being developed with the goal to reduce systematic uncertainties in the prediction of number of events at the far detector Super-Kamiokande. The upgrade program includes the design and construction of a new highly granular fully active scintillator detector with 3D WLS fiber readout as a neutrino target. The detector of about \(200 \times 180 \times 60\) cm\(^3\) in size and a mass of \(\sim 2.2\) tons will be assembled from about \(2 \times 10^6\) plastic scintillator cubes of \(1 \times 1 \times 1\) cm\(^3\). Each cube is read out by three orthogonal Kuraray Y11 Wave Length Shifting (WLS) fibers threaded through the detector. A detector prototype made of 125 cubes was assembled and tested in a charged particle test beam at CERN in the fall of 2017. This paper presents the results obtained on the light yield and timing as well as on the optical cross-talk between the cubes.

Keywords: T2K experiment, scintillating fiber detector, neutrino detectors, particle tracking detectors

1. Introduction

The long baseline neutrino experiment T2K\textsuperscript{[1]} taking data at the Japan Proton Accelerator Research Complex (J-PARC) has obtained a first hint on CP violation in neutrino oscillations and excluded CP conservation at a level of significance of 2 standard deviations\textsuperscript{[2]}. The T2K collaboration expects to collect higher statistics, thanks to planned upgrades to the J-PARC and the neutrino beamline, and reach a sensitivity of more than 3\(\sigma\) to CP violation observation. An upgrade of the T2K near detector ND280 for the run extension is currently being designed with the goal to reduce systematic uncertainties in the prediction of number of events at the far detector Super-Kamiokande.

The upgrade program of ND280 includes the development of a new highly granular fully active scintillator neutrino detector as a neutrino target. The ND280 fine-grained detectors (FGD) were designed as arrays of scintillator bars disposed perpendicular to the beam axis. Geometry was optimized to detect particles propagating in the forward direction, resulting in a dependence of acceptance and resolution on the lepton scattering angle for the neutrino events. It is also important to study the effect of nuclear activity by measuring the energy deposited by additional nucleons originating from the interaction or resulting from nuclear breakup. In this context the natural granularity scale must be around 1 cm, corresponding to the range in plastic of protons with momentum commensurate with the Fermi motion of about 220 MeV/c.

To obtain a more isotropic response and improve the localization of the neutrino interaction vertex, a new scintillator detector with 3D fiber readout was proposed as a neutrino target. The basic concept and design of this novel highly granular fully active detector (superFGD) are described in \textsuperscript{[3]}. The SuperFGD concept is illustrated in Fig. 1.

The SuperFGD for T2K is foreseen with dimensions of \(\sim 200 \times 180 \times 60\) cm\(^3\) and a total mass of about 2.2 tons. The detector will be assembled of more than 2 millions small cubes of \(1 \times 1 \times 1\) cm\(^3\). Each cube has three orthogonal through

Figure 1: Schematic view of the superFGD conceptual design. An array of 2x2x2 scintillator cubes illustrates the 3D readout by Wave Length Shifting (WLS) fibers.
holes of 1.5 mm diameter. The signal readout from each cube is provided by three 1.0 mm Kuraray Y11 multiclad WLS fibers [5] connected at one end to micro-pixel avalanche Hamamatsu MPPC photodiodes. A single fiber reads out a whole line, row or column of cubes so that the total number of readout channels is 58800. By using the time and pulse height information from the fired fibers in all $x-y-z$ directions, the real hit cubes can be determined with little ambiguity for neutrino events in the GeV energy region, thus providing the 3D track coordinates with an accuracy given by the cube size.

The structure of the superFGD allows to make small prototypes to determine the operational performance of the actual detector. A small prototype of superFGD comprised of 125 cubes was tested in a beam of charged particles at CERN in October, 2017. Light yield, cross-talk, and time resolution are presented in this paper.

2. Prototype design and experimental setup

More than 10k cubes were produced at UNIPLAST Co. (Vladimir, Russia) to assemble mock-ups and prototypes. At the initial stage of R&D the cubes were cut in size $1 \times 1 \times 1\, \text{cm}^3$ out of long 1 cm thick extruded slabs. For the real detector we plan to use the another production method of cubes, injection molding, which is now under development. Both methods provide the same light yield, the main differences are in manufacturing cost of large quantities of cubes, and in the reproducibility of geometrical size. The scintillator composition is polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP. After fabrication the cubes are covered by a reflecting layer by etching the scintillator surface in a chemical agent. The etching results in the formation of a white polystyrene micropore deposit over the scintillator [4].

The thickness of the reflector layer is within 50–80 $\mu\text{m}$. Three orthogonal through holes of 1.5 mm diameter were drilled in the cubes to accommodate WLS fibers as shown in Fig. 1.

A 5×5×5 array of 125 cubes is shown in Fig. 2. No additional layers between cubes were used, only outer protective skin made of thin hard material and adhesive tape. 75 WLS fibers were inserted through the cubes, protruding 3–4 cm out of the scintillator. The fibers are 1 mm diameter Y11(200) Kuraray S-type of 1.3 m length. One end of the fiber is attached to a photosensor, another end is covered by a reflective Al-based paint (Silvershine). The photosensors are Hamamatsu MPPCs 12571-025C with a $1 \times 1\, \text{mm}^2$ active area and 1600 pixels.

We applied sequentially in the beam test two types of front-end electronics. All channels were read out by multi-channel boards developed on the basis of the OMEGA "CITIROC" ASIC for the Baby MIND spectrometer [6]. These electronics boards provide a no-dead-time readout of the detector in a 2.5 ns time slots, allowing convenient selection and reconstruction of tracks. In order to measure the main parameters of the prototype with a high time resolution, we used custom made preamplifiers and the 16-channel CAEN digitizer DT5742 with 5 GHz sampling rate and 12-bit resolution. All results reported in this paper are hereafter obtained with the digitizer information.

Two small scintillator trigger counters of $3 \times 3 \times 10\, \text{mm}^3$ size spaced at distance of 26 cm were installed before and after the prototype. Thus we were able to select minimum ionizing particles (MIPs) from the beam with the position accuracy of about 3 mm. One of the trigger counters sent a signal to start the digitizer, signals from another one were measured by the digitizer and used in off-line analysis. Also an anti-coincidence (AC) scintillator counter with $10 \times 10\, \text{cm}^2$ area and a 9 mm aperture for the beam entrance was mounted in front of the prototype to remove accidentals. Trigger and AC counters were read out by the same MPPCs 12571-025C. All MPPCs were selected to have close values of the bias voltage, so we were able to fix it to 67.5 V recommended by Hamamatsu in the specification. In total, the digitizer reads out 12 WLS fibers, as shown in Fig. 1, a small trigger counter and two channels from the AC counter. The layout of readout fibers allow us to measure the parameters of 9 cubes in the front layer and 9 cubes in the back layer of the prototype. All other fibers were in place but idle for analysis.

The test beam was held at T10 area of the CERN Proton Synchrotron (PS). The line transported 6 GeV/c positive particles of mixed composition (mainly positrons and protons) with a momentum resolution of $\sim 0.5\%$. A trigger rate of around 100 Hz has been set by closing the beam collimators in order to maximize the fraction of single-hit events.

3. Performance in the beam

3.1. Light yield

A beam scan with a step of 2 mm was done across 3 cubes in the horizontal direction. Fig. 4 shows the position of the beam center for the scan points, with respect to the position of vertical and horizontal fibers in a cube. Beam particles were localized by the trigger counters within the spot of about $3 \times 3\, \text{mm}^2$. The events were selected if the light yield in a small trigger counter was larger than 50 p.e. and the time difference between both trigger counters did not exceed 1 ns.

We have measured 13 scan points over a span of 25 mm, 3 cubes were scanned in the front layer along with 3 cubes in the back layer. Each cube was read out by two fibers to measure the
response as a function of the beam position. The signal charge was calculated as the area of signal waveform normalized to the signal obtained for a single photoelectron (p.e.). Calibration coefficients were calculated for each run thanks to the excellent single photoelectron response of MPPCs. The result of the scan for the front layer is presented in Fig. 5.

Edge effects at the cube boundaries were minimized by selecting events with a light output exceeding the average crosstalk in both vertical and horizontal fibers. Although the beam spot is comparable to the cube size, we can observe a systematic increase in light yield when the beam point gets closer to the vertical fiber. The horizontal fiber demonstrates fluctuations of the light signal within measurement accuracy.

The light yield ($L_Y$) for different channels varies from 36 to 50 p.e./MIP for a single fiber. The typical $L_Y$ was close to 40 p.e./MIP/fiber, and the total $L_Y$ from two fibers in the same cube was measured on an event-by-event basis to be about 80 p.e., as expected.

### 3.2. Optical crosstalk

Since the white chemical reflector, like any reflector of the diffuse type, does not fully isolate the scintillation light, the leakage of light from a fired cube to the neighboring ones was investigated. Crosstalk was measured on an event-to-event basis as the ratio of signals in adjacent cubes to the signal in the fired cube. The average of the distribution of these ratios was defined as the average crosstalk. Accidental and induced electronic noise increase the pedestal fluctuations and create a false crosstalk. To suppress this contribution we considered the signal less than 0.5 p.e. as a zero value (pedestal). The dark noise of the MPPCs generates accidental single p.e. signals. We have measured that the dark noise adds less than 0.2% to the total value of crosstalk, thanks to the low level of dark rate of MPPCs ($\sim 100$ kHz typical value).

Fig. 6 shows the crosstalk distribution when the light from the cube CH0/CH4 leaks into the cube CH1/CH4 (see Fig. 3 for the channel labelling). The crosstalk was calculated as the ratio $L_Y_{CH1}/L_Y_{CH0}$. The crosstalk average value is 3.7%, while the average of $L_Y_{CH0}$ is 41 p.e. The crosstalk with values higher than 30% can be explained by shower events.

The crosstalk in four directions is shown in Fig. 7 when the beam hits the central cube CH1/CH4 in a $3 \times 3$ array. The average crosstalk is 3.4% per side. The average of the total crosstalk into all 4 sides on an event-to-event basis was measured to be 13.7%. From this we can conclude that 20% of the detected scintillation light escapes the fired cube into adjacent cubes through the cube reflective walls.

### 3.3. Time resolution

We have applied the constant fraction method to obtain the timing mark of the signal waveform. The preamplifiers extend the signal front to 7 ns (measured between 0.1–0.9 fractions of the amplitude), so that we have up to 40 digitizer sample points spaced at 200 ps at the front. The following procedure was used...
for each waveform to obtain the timing. First, the baseline was determined by fitting the first sample points before a signal with a horizontal line. Then a maximum amplitude of the waveform was measured. We have found that a fraction of 10% of the maximum amplitude at the signal front provides the best timing, so the next step was to determine which point on the time axis intercepts the amplitude level of 10% of the maximum.

Two options were exploited to get this time mark. First one is to find the first closest sample point at time axis which corresponds to the calculated value of 0.1 of the maximum. A more precise but more complicated option requires extrapolation between two closest sample points on the time axis which correspond to the amplitudes below and above the level of 0.1 of the maximum. The second method provides slightly better timing at the digitizer sampling rate of 5 GHz, and the advantage becomes more significant at the slower rates. The digitizer itself generates a time jitter correlated in all the channels. Leakage from a fired cube into adjacent cubes through the cube reflective walls. About 20% of the detected scintillating light escapes a fiber. About 20% of the detected scintillating light escapes a fiber.

0.95 ns. A cube with two readout fibers gives \( \sigma_T = 0.65-0.71 \) ns. Two cubes combined produced typical \( \sigma_T = 0.52 \) ns for the first method of the time mark calculation, and \( \sigma_T = 0.48 \) ns for the second method.

4. Summary

The superFGD prototype with 3D fiber readout was assembled of 125 plastic scintillator cubes of \( 1 \times 1 \times 1 \) cm\(^3\) size and successfully tested in a charge particles beam at CERN. Hamamatsu MPCCs viewed 1.3 m long 1 mm diameter WLS fibers Kuraray Y11 at a single end. A 5 GHz digitizer was used to read out 12 fibers out of 75 mounted ones to measure the parameters of the prototype.

Typical light signal in a cube was about 40 p.e. per a single fiber. About 20% of the detected scintillating light escapes a fired cube into adjacent cubes through the cube reflective walls. Leakage from a fired cube into a neighboring cube through a side was found to be between 3.5–4.0%. Typical time resolution for a single fiber was around 0.95 ns. A cube with two readout fibers gives \( \sigma_T = 0.65-0.71 \) ns and two cubes with four fibers produced typical \( \sigma_T = 0.48 \) ns.

We plan to expose a superFGD prototype made of 9200 cubes in a CERN test beam in summer 2018, where tracking capabilities of the detector will be investigated.
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