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Development of the in-situ Calibration System using LEDs and Light Guide Plates for the SuperFGD

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Abstract. T2K is a long-baseline neutrino experiment that aims to investigate the CP violation in the neutrino sector. An upgrade of the ND280, which is one of the T2K near detectors, is in progress. The active target detector of the upgraded ND280 is a segmented highly granular plastic scintillation detector (SuperFGD) consisting of about two million scintillator cubes. About sixty thousand silicon photo-multipliers (SiPMs) coupled with wavelength shifting fibers are used for light readout. The fibers go through the scintillator cubes along the orthogonal three directions. We developed a novel system based on LEDs and notched light guide plates for in-situ calibration of the SuperFGD. The developed system can distribute LED light to SiPMs simultaneously with high uniformity and can be used for gain calibration and stability monitor of the signal readout. In addition, it can fit in the confined space of the SuperFGD due to its thin structure. In this paper, we report the design and the performance of the calibration system.

1. The T2K experiment

T2K (Tokai-to-Kamioka) is a long baseline neutrino oscillation experiment using ν_μ or $\overline{\nu}_\mu$ beam from J-PARC to the Super-Kamiokande detector with 295 km baseline [1]. A current main purpose of the T2K experiment is to measure the CP phase $\delta_{\rm CP}$ from $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearances. Recent T2K results showed an indication of the neutrino CP violation from data collected until 2018 [2]. Upgrades of the J-PARC accelerators and one of the T2K near detectors, called ND280, are in progress to reduce both statistical and systematic uncertainties. The ND280 is located in the same direction as the Super-Kamiokande detector and at a distance of 280 m from the graphite target for the neutrino beam production. The ND280 measures flux of the neutrino beam before oscillations and measures the neutrino interaction precisely.

2. ND280 upgrade and SuperFGD

A schematic drawing of the ND280 upgrade is shown in Figure 1. The pi-zero detector (P0D) placed at upstream of the current ND280 will be replaced with new detectors. The new detectors consisting of SuperFGD, two High-Angle TPCs, and six Time of Flight planes will be installed in 2022 [3, 4].

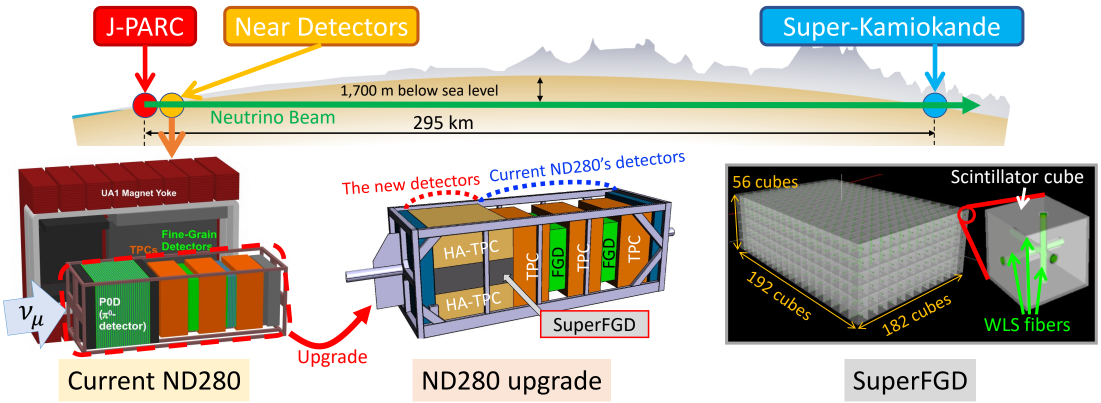

Figure 1. A schematic drawing of the T2K near detector complex in J-PARC. From the left, current ND280, ND280 upgrade concept, and SuperFGD in the upgraded detector are shown.

The SuperFGD [5] is a highly granular scintillation tracker. The SuperFGD is composed of $192 \times 182 \times 56$ plastic scintillator cubes with a size of $1 \times 1 \times 1$ cm^3. The total active target mass of the SuperFGD is approximately 2 tons. The scintillator cubes are made of polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP, with a reflecting layer within 50$\sim$80 μm thickness, and produced by UNIPLAST Co. (Vladimir, Russia). Each of the cubes has three orthogonal holes, and about sixty thousand wavelength shifting (WLS) fibers go through the holes of the cubes. The scintillation light generated inside a cube is absorbed by the WLS fibers, and re-emitted light is lead to the SiPM coupled to the fiber end. The SuperFGD can track charged particles as projections onto three directions and then provides good particle identification performances [6, 7]. Y-11 (MS) type WLS fibers manufactured by Kuraray Co., Ltd. and SiPMs S13360-1325PE from Hamamatsu Photonics K.K. are used in the SuperFGD.

3. Concept of the SuperFGD Calibration system

One of the purposes of the calibration system using LEDs is to calibrate gains of SiPMs including electronics, and the other purpose is to monitor the stability of the signal readout. The calibration system is required to inject light to a large number of SiPMs simultaneously from the end of fibers. In addition, a thin structure and uniform light distribution are required

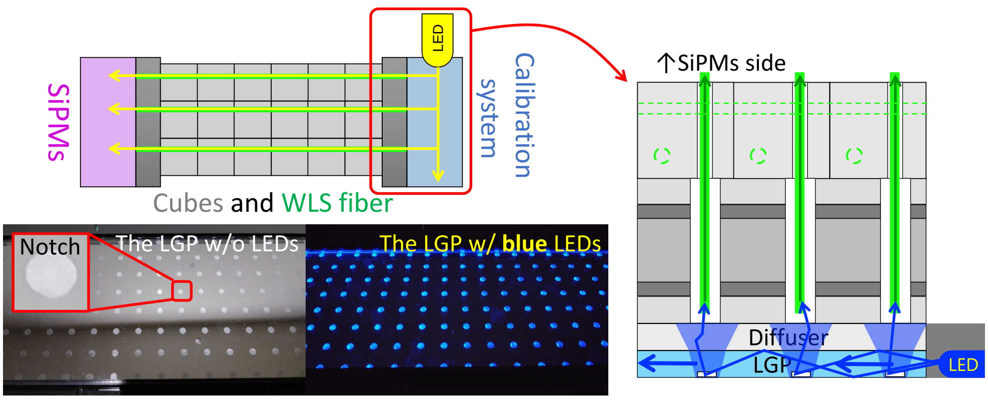

Figure 2. Conceptual drawing of the light injection method for a large number of channels and a picture of the LGP prototype.

for the system.

We adopted light guide plates (LGPs) for the optical distributor. The LGP is made of a transparent acrylic plate with laser dotted notches arrayed at the same pitch as the fibers. It has an ability to distribute light two-dimensionally to a large area utilizing light scattering at the notches as shown in Figure 2. The LGP can cover a lot of SiPM channels with low cost and a small amount of LEDs under spatial restriction.

The LGP is modularized with a diffuser, LEDs, an LED collimator, a container, and other small parts as shown in Figure 3. The LGP modules are attached to the bottom and the sidewall of the SuperFGD by screws. To cover all SiPM channels located in different directions, we develop two types of LGP modules: one is bottom LGP module whose dimension is $999.5 \times 81.1 \times 8.0$ mm, and the other is wall LGP module whose dimension is $569.4 \times 81.1 \times 8.0$ mm. We use 46 bottom LGP modules and 47 wall LGP modules to cover all SiPM channels.

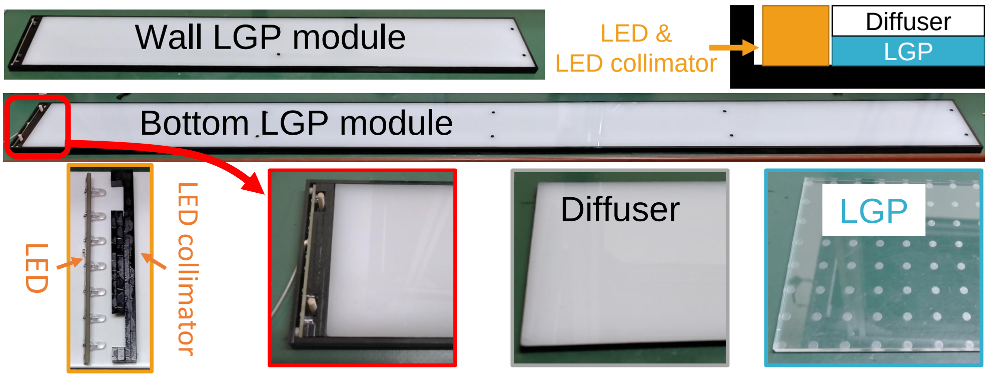

Figure 3. The pictures of the LGP modules and their components. The wall and bottom LGP modules are shown at the top. Components are shown at the bottom. A cross-sectional drawing of the module is shown at the top-right.

The LGP modules are connected to the LED driver boards, which control the LEDs, with micro coaxial cables. The LED driver board consists of amplifiers, an FPGA to control pulse height and duration, and an Ethernet board to communicate with the DAQ system. Eight LED driver boards in total are used to operate 651 LEDs and provide LED light for 55,888 channels.

4. The optimization of the LGP module

The components of the module are optimized to distribute light as uniform as possible.

The light source of the module is composed of 7 round-shape high-directivity blue LEDs (NSPB300B produced by NICHIA CORPORATION) that are arrayed on a LED-PCB. Each of the 7 LEDs is positioned at the middle of the 8 rows of the notches. For channels that are close to the light source, this LED arrangement with a light collimator provides the highest light uniformity.

Thickness of the LGP is chosen to be 3 mm which can save space without degrading performance. The diameter of the notches is set to be 3 mm, three times of the fiber diameter, to increase tolerance for a horizontal fiber displacement which causes a degradation of light yield. The depth of the notch is adjusted to approximately 0.01 mm to suppress light attenuation along the plate due to light scattering by the notches. The LGP edge opposite to the LEDs is painted black to prevent light increase at the far-end channels due to light reflection.

The diffuser lies on the LGP to diffuse light from notches in the LGP. In addition to enlarging notches, the diffuser can also increase tolerance of the horizontal fiber displacement. The diffuser is made of a translucent white acrylic plate. For saving space, the thickness of the diffuser is designed to be 3 mm which has enough diffusivity. The sides and screw holes of the diffuser are painted black to suppress light scattering at the channels that are close to the edges and screw holes.

5. The light yield of the LGP module prototype

Light uniformity of the module prototype was measured using a SiPM coupled to a fiber. The fiber end was placed at the center of each notch for the measurement. Figure 4 shows the measurements of the relative light yields for the bottom module prototype. We obtained a factor of 2.41 (2.38) for the bottom (wall) module as a ratio of the highest to lowest light yields. By taking into account the horizontal (vertical) fiber displacement, which decreases light yield down to 96.3% (85%), we expect that the LGP module can distribute light within a factor of 2.9 to all channels.

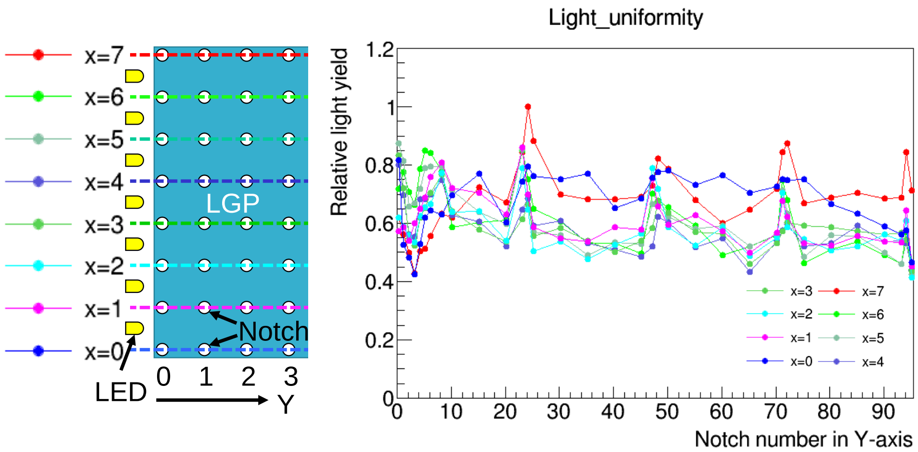

Figure 4. Measurement of light uniformity for the bottom module prototype. The vertical axis shows relative light yield which is normalized by maximum light yield, and the horizontal axis shows notch number in Y-axis as illustrated in the left. The color represents different rows on the plate as also illustrated with dashed lines in the left.

6. Summary

We developed the novel LED calibration system utilizing the LGP. The design was optimized to distribute light for many channels simultaneously and uniformly under the restrictions of the space, cost, and a few number of light sources. The system is successfully designed with the module thickness of 8 mm to distribute light within a factor of 2.9 to all channels. Production with the final design starts soon toward the upgraded detector installation. This study can find applications in detectors of a similar configuration.

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