R&D on an Innovative Silicon Photomultiplier-based Calibration System for the T2K Scintillator Tracker Detector

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Abstract

The T2K collaboration decided to upgrade the ND280 to collect enough statistics to search for CP violation. In order to reduce the neutrino oscillation systematic uncertainties, a new highly granular, fully active scintillator detector SuperFGD with a light readout interface based on Silicon Photomultipliers (SiPM) is introduced. As the SiPMs characteristics depend on voltage and temperature, a calibration system to achieve consistent measurements across all channels and to monitor the SiPM performance as a function of time is crucial. The conceptual design is similar to the technique proposed for the CALICE collaboration – notched fibres. To show the feasibility of the LED-based calibration system with notched fibres on a wavelength shifting (WLS) fibre readout system, the light-yield of two notched squared $1 \times 1 \text{ mm}^2$ fibres with double cladding, clear Saint-Gobain and WLS Kuraray, were measured obtaining satisfactory results with the light yield relatively uniform along the fibre. Furthermore, a possible integration in the SuperFGD mechanical box was demonstrated.
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1 Introduction

1.1 The T2K Experiment

T2K is a long-baseline neutrino oscillation experiment in Japan that studies neutrino oscillations through the muon neutrino disappearance and electron neutrino appearance channels. The goal is to observe a first evidence of the CP violating phase ($\delta_{CP}$) and perform world-leading measurements of the oscillation parameters $\Theta_{23}$ and $\Delta m^2_{32}$ ($\Delta m^2_{13}$), see [1].

Neutrinos (antineutrinos) are produced during the decay of pions and kaons created by collisions between a 30 GeV proton beam and a graphite target at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai. A Near Detector (ND) positioned 280 m far away from the production target detects the muon neutrinos before they had chance to oscillate. The Far Detector (FD) Super-Kamiokande detects neutrinos approximately in the position of the oscillation probability maximum. Both ND and FD are positioned 2.5° off-axis to provide a narrow band neutrino beam, peaking around 600 MeV [2].

1.2 The Upgrade of the Near Detector

The T2K Collaboration has decided to extend the data taking until 2025 to collect enough statistics to search for CP violation [3]. However, the neutrino interaction systematic uncertainties are a big limiting factor. Thus, the T2K Collaboration is planning to improve the off-axis ND (ND280) by introducing a new scintillator detector (SD) with traverse system of time projection chambers (TPCs) surrounded by time of flight detectors (TOF detectors), see Fig.: 3 (a). This upgrade will improve the detection efficiency for the angular acceptance and allow better determination of $t_0$. As shown in Fig.: 2, upgrading ND280 will allow to test the CP-conserving hypothesis with a significance of 3\sigma.
Figure 2: Sensitivity to CP violation as a function of protons on target. The systematic uncertainties corresponding roughly to [4] are compared to the case of 4 % systematic uncertainties on all the SuperKamiokande samples, as can be conservatively estimated in T2K-II using the constraints from ND280 upgrade.

The SD consists of a novel idea proposed in [3]. It is a Super Fine-Grain Detector (SuperFGD), a fully-active plastic scintillator detector (192 × 192 × 56 cm$^3$) made of many 1 × 1 × 1 cm$^3$ optically isolated, polystyrene cubes. Wavelength shifting (WLS) fibre will readout the light along the 3 orthogonal directions $x$, $y$ and $z$, as shown in Fig.: 3 (b) and (c).

As a charged particle passes through plastic cubes and deposits energy, scintillation light is produced, trapped in the cube, captured by WLS fibres and carried up to Silicon Photomultipliers (SiPMs) that count the number of photons produced. This geometry provides a 3D reconstruction tracking information and also identification of the particle based on the amount of light produced (Fig.: 4).
2 Silicon Photomultipliers (SiPM) Characteristics

The SiPMs that are planned to be used as a light readout interface for SuperFGD are Multi-Pixel Photon Counters (MPPCs) produced by Hamamatsu Photonics, similar to the ones that have been already successfully used in ND280.

The MPPCs, photosensors for scintillation light detection, are solid state silicon detectors with a single photon counting capability based on arrays of single photon avalanche diode (SPAD) operating in a reverse-bias voltage well above the breakdown voltage (Geiger mode). To increase the carrier population of the original photo-carrier count to a level that can be adequately readout, the impact ionisation effect constituting of a carrier multiplication (avalanche effect) is utilised.

The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor. One MPPC is made of a large number of these pixels that are electrically connected and arranged in two dimensions. Each pixel in the MPPC outputs a pulse at the same amplitude when it detects a photon. Pulses generated by multiple pixels are output while superimposed onto each other. Each pixel outputs only one pulse and this does not vary with the number of incident photons, so the number of output pulses is always one regardless of whether one photon or two or more photons enter a pixel at the same time. This means that MPPC output linearity gets worse when the number of incident photons approaches the number of MPPC’s pixels. This makes it essential to select an MPPC having enough pixels to match the number of incident photons [5].

<table>
<thead>
<tr>
<th>Type no.</th>
<th>Pixel pitch (μm)</th>
<th>Effective photosensitive area (mm²)</th>
<th>Number of pixels</th>
<th>Package</th>
<th>Fill factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S13360-1350CS</td>
<td>50</td>
<td>1.3 x 1.3</td>
<td>667</td>
<td>Ceramic</td>
<td>74</td>
</tr>
<tr>
<td>S13360-1350PE</td>
<td></td>
<td>3.0 x 3.0</td>
<td>3600</td>
<td>Ceramic</td>
<td></td>
</tr>
<tr>
<td>S13360-3050CS</td>
<td></td>
<td>6.0 x 6.0</td>
<td>14400</td>
<td>Ceramic</td>
<td></td>
</tr>
<tr>
<td>S13360-3050PE</td>
<td></td>
<td>6.0 x 6.0</td>
<td>14400</td>
<td>Surface mount</td>
<td></td>
</tr>
<tr>
<td>S13360-6050CS</td>
<td></td>
<td>6.0 x 6.0</td>
<td>14400</td>
<td>Surface mount</td>
<td></td>
</tr>
<tr>
<td>S13360-6050PE</td>
<td></td>
<td>6.0 x 6.0</td>
<td>14400</td>
<td>Surface mount</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: MPPC specification (Hamamatsu) [5]
MPPCs are highly sensitive to temperature and input voltage changes with each individual MPPC having slightly different operating voltage. Using MPPC for precision measurements, it is crucial to understand the MPPCs characteristics such as dark count rate (DCR), crosstalk and gain, and their dependence on input voltage and temperature:

- **DCR**: pulses produced in absence of light due to thermal agitation
- **Crosstalk**: activation of neighbouring cell by one of the multiplication carriers crossing the boundary
- **Gain**: number of electrons created when the avalanche is triggered by a photon, i.e. area gain obtained by integrating the area of signal pulses

![Table Image]

These characteristics were tested using one of the MPPCs for precision measurements (S13360-1350) with a similar topology to the ones that are planned to be used in the SuperFGD. They consist of an array of, specifically in this case, 667 pixels and are available in two types: ceramic (CS) and surface mounted (PE), see Fig.: 7 (a) and (b). There is no difference expected in the performance of these two types.

![Images (a) and (b)]

Specifically for the measurements described, a ceramic MPPC S13360-1350CS (Hamamatsu Serial No.: 15849) with optimal operating voltage of 55.92 V at 25 °C, defined by Hamamatsu as $V_{breaking} = V_{op} + 3$ Volts, was tested.
In the SuperFGD, the MPPCs used will be mounted on a printed-circuit board (PCB) for compactness. As this type of MPPC is sensitive to green light (550 nm), green LED was placed in a close proximity to the MPPC.

The measurement setup was based on Hamamatsu Driver Circuit (Fig.: 8), a simple evaluation starter kit which can be controlled by PC using the sample software provided (Fig.: 9 (a)). It allows to set the operating voltage and also includes a temperature controller. The signal detected by MPPC can be visualised and measured via oscilloscope. The measurement of DCR (Fig.: 9 (b)), crosstalk and gain was carried out for two different temperatures, placing the entire setup to a temperature-controlled chamber.

![Driver Circuit based MPPC measurement setup](image)

Figure 8: Driver Circuit based MPPC measurement setup [6]

![Driver Circuit software interface](image) ![Single photoelectron (p.e.) waveform changes](image)

Figure 9: (a) Driver Circuit software interface; (b) Single photoelectron (p.e.) waveform changes for different operating voltages (for no input LED light)
2.1 Dark Count Rate (DCR)

The DCR pulses are produced in absence of light due to thermal agitation, thus the measurements were carried out with no input from the green LED. DRC dependence on operating voltage was measured at two different temperatures of the temperature controlled chamber – room temperature ($\sim 25^\circ$C) and 8.81 $^\circ$C. The MPPC’s temperatures corresponding to the controlled chamber temperature were read out using the Hamamatsu Driver Circuit software to be 26.26 – 26.73 $^\circ$C and 11.82 – 11.92 $^\circ$C, respectively, as the temperature of the MPPC increases with increasing operating voltage.

Hamamatsu provides a packaging information that the typical DCR is expected to be about 90 kHz (at 25 $^\circ$C and at the optimal operating voltage $\sim 56$ V ), see Fig.: 5. At room temperature, the DCR observed in the measurement was about 65 kHz (for the optimal operating voltage $\sim 56$ V), which is in a good agreement with the expected value. For the measurement at 8.81 $^\circ$C, the DRC was observed at 22 kHz. That is, as expected, less than the value at room temperature, as the decreased temperature decreases the thermal vibrations in the silicon lattice. (Fig.: 10)

The measurements were obtained by setting a threshold of 0.5 photoelectron (p.e.) to exclude the electronic noise.

![Figure 10: (a) DRC dependence on operating voltage at room temperature (MPPC: 26.26 – 26.73 $^\circ$C; (b) DRC dependence on operating voltage at 8.81 $^\circ$C (MPPC: 11.82 – 11.92 $^\circ$C)](image)

2.2 Crosstalk

The crosstalk is an activation of a neighbouring cell (pixel), i.e. noise caused by photon crossing a PN junction and triggering avalanche process in the neighbouring cell. Thus, in the MPPC, there is a certain probability that one incoming photon can output a pulse from more than one pixel. This process increases with increasing operating voltage and temperature depending on the junction capacitance.

For the measurement, the trigger was set at about 1.5 p.e. to exclude the DRC, and the crosstalk was expressed as % of DRC, taking the ratio of crosstalk and DRC:

$$X_{\text{talk}} (\text{DRC } \%) = \frac{\text{Rate}_{X\text{-talk}}}{\text{Rate}_{\text{DRC}}}$$  \hspace{1cm} (1)
Hamamatsu provides an information that the crosstalk for an optimal operating voltage at room temperature should be around 3 % (Fig.: 6). In the measurement, the crosstalk observed was in a good agreement with the expected value – about 2.7 %. The crosstalk rate was found to be approximately constant, comparing the values of the measurement at room temperature and at 8.81 °C for the same operating voltage, see Fig.: 11.

![Figure 11](image)

Figure 11: (a) X-talk dependence on $V_{op}$ at room temperature (MPPC: 26.26 – 26.73 °C; (b) X-talk dependence on $V_{op}$ at 8.81 °C (MPPC: 11.82 – 11.92 °C)

### 2.3 Gain

The gain is the number of electrons created when the avalanche is triggered by an incoming photon, i.e. area gain obtained by integrating the area of signal pulses. Therefore, the measurement of the gain of the MPPC and its dependence on the operating voltage was carried out by pulsing green LED ($\sim 10$ kHz rate and 30 ns pulse width).

Using an oscilloscope, the histogram of charge distribution (p.e. peaks) $Q/Z_{\text{input}}$ was obtained by integrating the area under the signal, where $Z_{\text{input}}$ is the impedance of the scope (50 Ohm). Then, a multi-Gaussian fit was performed to extract the distance between the p.e. peaks. Dividing the distance between the peaks by electron charge $e$ and the circuit amplification $F_{\text{amp}}$ (10), the gain for each individual voltage was obtained:

$$gain = \frac{Q}{e \times Z_{\text{input}} \times F_{\text{amp}}}$$

(2)

The entire extraction process is represented in Fig.: 12.

The minimal gain at room temperature expected by Hamamatsu is $1.70 \times 10^6$ (for optimal operating voltage), see Fig.: 6. The gain extracted, corresponding to the room temperature and the same optimal operating voltage, was about $2.09 \times 10^6$ which is in a good agreement with the value expected. For the measurement at lower temperature, the gain extracted was higher, $2.63 \times 10^6$ (for the same operating voltage), as the gain increases with decreasing temperature due to decreased phonon vibrations and thus lower loses in a kinetic energy of avalanche carries (decrease in scattering collisions), see Fig.: 13.
Fitting the gain values extracted vs. the operating voltage, the breaking voltage of the MPPC can be obtained by reading off the intercept of the straight line fit with operating voltage axis. For the room temperature measurement, the expected breaking voltage provided by Hamamatsu is 52.92 V which is in a good agreement with the observed breaking voltage of 53.11 V (Fig.: 13).

Also given by Hamamatsu, there is about 50 mV/°C dependence on operating/breaking voltage. Considering the difference between the MPPC’s working temperatures, the expected breaking voltage for the lower temperature measurement is about 52.40 V. The observed breaking voltage was extracted to be 52.36 V which is, again, in a very good agreement with the predicted value (Fig.: 13).
3 R&D for the SuperFGD Calibration System

As demonstrated in Section 2, the MPPCs are highly sensitive to temperature and input voltage changes. Moreover, the optimal input voltage can vary depending on the particular MPPC. Thus, a calibration system to achieve consistent measurement across all channels and to monitor the MPPC performance as a function of time is crucial. The concept of the calibration system is to produce a known amount of LED light, distribute it through WLS fibres to MPPCs and compare the uniformity of response so the individual MPPC can be calibrated.

The conceptual design to distribute the LED light for the calibration system effectively involves a technique proposed for the CALICE detector, as shown in Fig.: 14 and Fig.: 15 (a). The light is injected from the one side of the light guide, e.g. clear fibre, and when it encounters a notch, it is in part scattered and exits the fibre at about 90°.

The notch is a special scratch on the fibre precisely made by hot touch [7]. It allows the light distributed by the clear fibre to move to the WLS fibre and towards the MPPC. The size of the notches varies as a function of the distance, maintaining the homogeneity of the light yield. The notched fibres used in the following measurements were made by colleagues in FZU in Prague.

![Figure 14: (a) Principle of the light emitted by the notch; (b) First notch, closest to the LED; (c) Last notch, at the rear fibre end; (d) Light spot from the notch emission](image1)

![Figure 15: (a) Notched fibre; (b) Coupling of the notched fibre to the WLS and MPPC](image2)
One of the challenges of this approach is the idea to couple the notched fibre with WLS fibre, see Fig.: 15 (b). In previous tests, the LED light was injected through the end of the fibre, see Fig.: 16 (a). This approach turned out to be problematic due to a possible mechanical deformation (mechanical sagging) of the box, where the LED calibration system is integrated. It was shown that there is a weak tolerance on WLS fibre end – notch distance. As the precise alignment is a key to retrieve an uniform light yield, another approach had to be proposed.

The solution was to inject the light through the WLS fibre double-cladding which has about 5 % capture efficiency (Fig.: 16 (b)). This results in a lower light yield with respect to the original idea but it is still sufficient for the calibration purposes. The light yield could be enhanced by about 30 % by using a tyvek reflector at the end of the WLS fibre which would reflect the light possibly exiting the fibre from the end not coupled to the MPPC. In that case, the original idea is no longer possible.

For calibration purposes, the light-yield of each notch and its uniformity along the fibre was to be measured (in visible p.e.) with the goal to clearly observe p.e peaks. The measurement was performed on two different fibres, Saint-Gobain Clear Squared 1 × 1 mm² fibre and Kuraray WLS Squared 1 × 1 mm² fibre, both with double cladding and 24 notches of pitch every 3 cm.
3.1 Preliminary Test: Sain-Gobain Fibre

The preliminary measurement was performed using the clear notched Saint-Gobain Squared $1 \times 1 \text{ mm}^2$ fibre (double cladding). Green light was produced with LED and injected through the end of the notched fibre, and the response was read out using front-end boards, see Fig.: 17. The number of p.e. for Saint-Gobain fibre was mostly uniform with slight variation of few p.e., probably resulting from some notch–WLS fibre misalignment due to the setup and some scratches found along the fibre. As expected, a higher light-yield for the notches closest to the LED was also observed (Fig.: 18).

![Figure 17: Measurement setup with light-on-cladding configuration close-up](image1)

![Figure 18: Mean/gain p.e. vs. notch position for Saint-Gobain fibre (1st notch corresponds to the notch closest to LED)](image2)
3.2 Integration of the LED Calibration System

As the calibration system has to be very compact and fit the SuperFGD dimension requirements, an integration layer of the LED system is needed. A prototype that will be able to contain about 10 000 cubes, see Fig.: 19 (a) and (b), is currently under construction at CERN. Except providing the desired compactness, it will also fix the notched fibre position, i.e. prevent it to rotate, and contribute to achieving a perfect alignment of the notch and WLS fibre thanks to a square groove. This is really important as the notches are directional and any misalignment would result in lowering the light-yield, and worsen the uniformity of the light exiting the different notches.

To test a part of a possible integration in the SuperFGD mechanical box, a square groove based on the actual prototype was design in CAD, see Fig.: 19 (c). The square groove was designed to have dimensions about $150 \times 50 \times 6.5 \text{ mm}^3$ (to accommodate 5 notches), and it was 3D printed at CERN polymer laboratory with cca 0.2 mm tolerance, see Fig.: 19 (d).

Figure 19: (a) and (b) Compact LED calibration system, NP07 prototype; (c) Square groove $150 \times 50 \times 6.5 \text{ mm}^3$ (accommodates 5 notches): CAD model; (d) 3D printed prototype
3.3 Kuraray Wavelength Shifting Fibre

Since the results with the clear fibre were satisfactory, it was decided to study features of a notched WLS fibre, i.e. with a longer attenuation length. Using the 3D printed square groove, a measurement of the light-yield of Kuraray WLS Squared $1 \times 1 \text{ mm}^2$ fibre (double cladding) was carried out.

The whole setup was moved into the dark room to eliminate any light residues from the surroundings. The fibre was also kept straight to follow the design of the integration in the SuperFGD, see Fig.: 20 (a). Employing the square groove piece into the apparatus, the possible misalignment of the notch and WLS fibre should be significantly reduced.

Considering the WLS nature of the fibre, the expectations for the light yield uniformity and the ability to observe p.e. peaks were not high. Yet, the measurement showed variation of only few p.e. with the uniformity of the notch light yield being still sufficient for the calibration goals, see Fig.: 20 (b).

![Figure 20: (a) Measurement setup (dark room), light-on-cladding configuration, printed groove for square fibre; (b) Mean/gain p.e. vs notch position for WLS Kuraray (1st notch corresponds to the notch closest to LED)](image)
4 Conclusions

For the T2K Near Detector upgrade, a novel idea of SuperFGD, fully active plastic SD, based on the MPPCs light readout interface was introduced. The MPPCs characteristics and their dependence on voltage and temperature were measured to show the reasoning behind the need of the calibration system. Furthermore, the feasibility of a LED-based calibration system with notched fibres on a WLS fibre readout system was demonstrated and a possible option for the integration in the SuperFGD mechanical box was tested. The results obtained were satisfactory with the p.e. peaks clearly observed, and with the light-yield relatively uniform along the fibre.

The next steps are to complete the detector prototype and finalise the design of the LED calibration system integration. It is also important to test the uniformity for a smaller pitch between the notches, i.e. 1 cm, and test the uniformity for LED – 1st notch distance cca 5 cm, i.e. what is expected in the SuperFGD box. These tests are to be performed with notched Kuraray Clear Squared 1 × 1 mm² fibre (double cladding).

References


