A new charged particle detector for the KOTO experiment at J-PARC

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Abstract. We installed a new detector called Downstream Charged Veto(DCV) in order to suppress the $K_L \to \pi^+\pi^-\pi^0$ decay background for the J-PARC KOTO experiment. Since the background is caused by non-detected charged pions passing through the beam hole of the electromagnetic calorimeter, the detector was installed in vacuum downstream of the calorimeter. The DCV is composed of two plastic scintillator pipes read out by Multi Pixel Photon Counters(MPPCs) through wavelength shifting(WLS) fibers. From the test by using cosmic-rays during its fabrication, we obtained more than 50 photoelectron per 1 MeV energy deposit at the center of the DCV. After its installation, energy calibration was done with cosmic-rays which is identified by detectors surrounding the DCV.

1. Introduction

The KOTO experiment at J-PARC is searching for the $K_L \to \pi^0\nu\bar{\nu}$ decay, which is one of the most sensitive probes to new physics beyond the standard model(SM). Its signature is a pair of photons from a π^0 decay without any additional activity in a hermetic detector system surrounding the decay region. To detect this highly suppressed decay, expected at the 3×10^{-11} level, it is important to reject background events related to other kaon decay modes. At the single event sensitivity of 1.30×10^{-9} achieved by data collected in 2015, the number of $K_L \to \pi^+\pi^-\pi^0$ background was estimated as 0.05 [1] which corresponds to 2 at the SM sensitivity. The decay becomes background when charged pions passing through the beam hole are not detected due to their interaction with non-active materials. According to a Monte Carlo(MC) simulation, as shown in Fig. 1, there are three materials where the π^+ and π^- interact and disappear. One is the membrane which separate decay region being evacuated as 10^{-5} Pa from the detector region where is relatively low vacuum level(10^{-2} Pa). The other source is square pipes made of 0.5-mm-thick G10 plates, which prevents the membrane from drooping down to beam. The last one is a beam pipe made of 10-mm-thick aluminum for extending the highly evacuated decay region far from the calorimeter. Since the DCV is able to support the membrane, we need not the G10 pipe anymore. However, the G10 pipe placed inside the calorimeter is still remained, however, its length was shortened.

To reduce the $K_L \to \pi^+\pi^-\pi^0$ background events, we have to detect the charged pions before they interact with those non-active materials. For the purpose, we decided to install a new charged particle detector, DCV, inside the high vacuum region downstream of the electromagnetic calorimeter. To minimize the non-detected area, the DCV is placed as close as possible to the electromagnetic calorimeter.

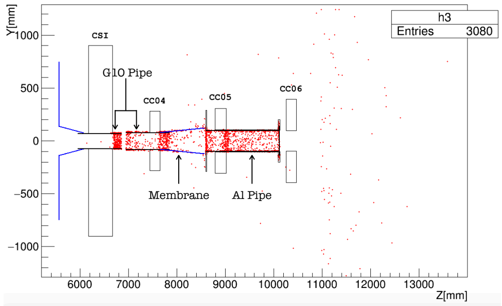


Figure 1. Interacting point of π^+ and π^-. Red dots indicate where the charged pions are disappeared.

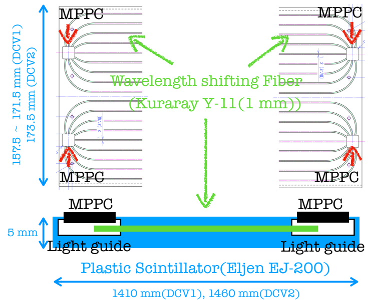


Figure 2. Configuration of scintillator with WLS fibers and MPPCs.

2. Structure of the DCV

The DCV consists of two successive square pipes, and each of them is made of 4 sheets of scintillators. The DCV1 is placed at 463 mm downstream from the calorimeter and inside the membrane. The DCV1 is a 1410-mm-long trapezoidal pipe has a square of side length as 157.5 mm at the upstream end and as 171.5 mm at the downstream end, respectively. On the other hand, the DCV2 is a 1460-mm-long square pipe having its side length as 173.5 mm. We made 18 grooves in a 5-mm-thick plastic scintillator (EJ200, Eljen Technology) in order to embed 1 mm diameter wavelength shifting(WLS) fibers(Y-11, Kuraray). For the light collection in the very limited space, the WLS fibers are routed into a light guide made of aluminum at the scintillator surface. Since the size of the light guide is 6 mm $\times$ 6 mm to fit the size of MPPC, the WLS fibers are needed to be bent to converge into the light guide as shown in Fig. 2. The radius of grooves are larger than 20 mm, because the light loss due to the curvature shows a rapid increase when the radius is smaller than 20 mm as shown in Fig. 3. The WLS fibers are grouped into two and read by MPPC(S13360-6050PE, Hamamatsu) at both ends of each group(4 read-out MPPCs in total).

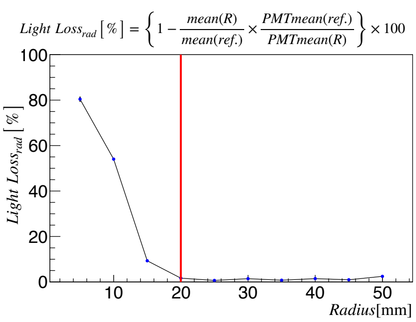


Figure 3. The light loss due to the curvature of the WLS fiber.

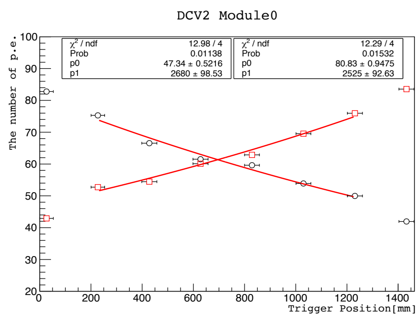


Figure 4. The number of p.e. at each cosmic-ray trigger point

3. Fabrication Process

The WLS fibers were glued to the plastic scintillator plate using the optical cement(BC-600, Saint-Gobain) and introduced to the light guide at the both-ends of the plate. All WLS fibers were tested their soundness by measuring light yield at the end of the fibers while a LED light(430 nm) illuminated at the other end of them. After waiting 48 hours for the optical cement to harden enough, we place the scintillator in a vacuum chamber evacuated less than 1 Pa in order to extract the outgas from the glued scintillators for longer than 48 hours. The scintillators were wrapped by a 12-μm-thick aluminized mylar and the MPPCs were respectively attached to the light guide and fixed by aluminum plates.

There are 4 MPPCs for each scintillator plate and they are operated by a common high voltage supplier. We measured MPPC's gain from the single-photon signal and arranged same-gain MPPCs for a given scintillator under the same operating voltage.

The light yield of the assembled scintillator was measured by using cosmic-rays triggered at 8 different points of the plates. As shown in Fig. 4, the average number of photoelectrons at the center of the scintillator was given as 50.2 for the DCV1 and 58.6 for the DCV2 according to energy deposit by cosmic-rays(1 MeV), and its attenuation lengths were found to be 2469 ± 165.1 mm for the DCV1 and 2566 ± 166.0 mm for the DCV2, respectively.

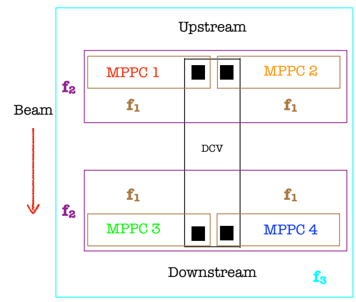


Figure 5. Three different gain factors for the DCV energy calibration with 4 MPPCs.

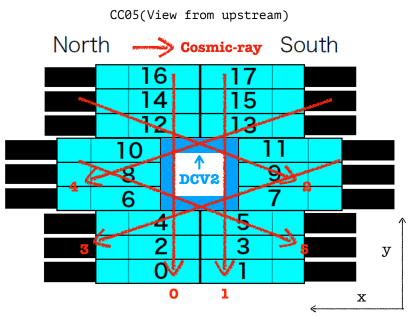
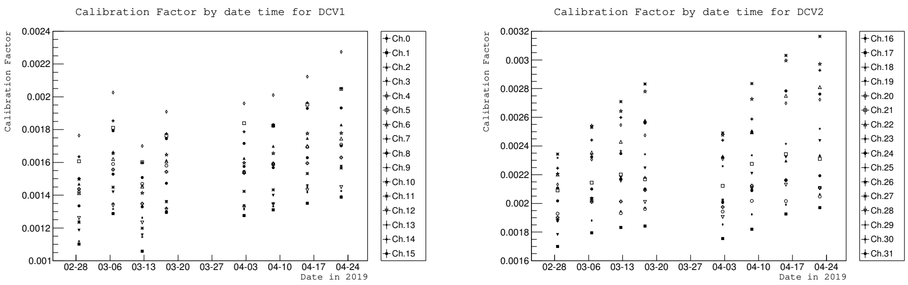


Figure 6. Tracks of the cosmic-rays identified by the CC05 for DCV2 calibration.

4. Energy Calibration

After the installation of the DCV into the KOTO detector system, we took the cosmic-ray data for its energy calibration. We used two detectors made of CsI crystals surrounding the DCV, the CC04 for the DCV1 and the CC05 for the DCV2, as trigger counter. We can select a track of the cosmic-ray by using the detectors as shown in Fig. 6, and we can estimate an energy deposit by the cosmic-ray in the DCV. Since the scintillation light was shared 4 MPPCs, we need to extract gain factors for them to produce an energy deposit after summing up. As the first step, we selected the tracks passing half parts of the DCV in which a clear peak in ADC distribution can be obtained. For example, track 1 was used to get a gain factor f_1 for MPPCs placed at south part for the top and bottom plates. Secondly, we corrected the effect of shower sharing(f_2) by summing up calibrated ADC values using the f_1 for two MPPCs for both ends individually and fitting again to the same function. Finally, we summed 4 calibrated ADC values applied the two factors(f_1 and f_2) at the same time and fit again to the same function. In this way, we got a gain factor f_3.

During the beam time from February to April in 2019, we collected the cosmic-ray data at beam break that occurred once per week. Figure 7 shows gain factors for whole MPPCs and variation according to time of data taking. The gain factors tend to increase over time which implies that the gain of MPPCs decrease. A detailed study on the variation is understudying.



(a) (b)

Figure 7. Calibration Factor over time for DCV1(a) and DCV2(b).

5. Summary

We fabricated and installed a new charged particle detector, the DCV, for further rejection of the background events from the $K_L \to \pi^+\pi^-\pi^0$ decay. Based on the cosmic-ray test performed during its fabrication, the light yield is more than 50 p.e. for 1 MeV energy deposit at the center of the DCV. We established a method of its calibration by using cosmic-ray identified by detectors surrounding the DCV. Studies on stability of its performance during the beam time is undergoing.

Acknowledge

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Reference

[1] J.K. Ahn *et al.* (KOTO Collaboration) 2019, *Phys. Rev. Lett.* **122** 021802