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

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Abstract. We report a performance of a new scintillator array, Downstream Charged Veto(DCV), to suppress the $K_L \to \pi^+\pi^-\pi^0$ decay background for the J-PARC KOTO experiment. Since the background originates from undetected 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(MPPC) through wavelength shifting(WLS) fibers. The light yield was found to be 60 photoelectrons/0.8 MeV in a test bench when cosmic-rays pass through the center of the DCV. Preliminary energy calibration was performed using cosmic-rays after installation in the beam line.

1. Introduction

The KOTO experiment at J-PARC aims to observe 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 events 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. A Monte Carlo simulation shows that most of π^+ and π^- particles disappear in three upstream sections, as illustrated in Fig. 1. One is the membrane which separates 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 placed inside the calorimeter and the CC04 separately, which prevents the membrane from drooping toward the beam axis. The last one is a beam pipe made of 10-mm-thick aluminum for extending the highly evacuated decay region far from the calorimeter.

To reduce the $K_L \to \pi^+\pi^-\pi^0$ background events, the charged pions should be detected before they interact with those non-active materials. In this respect, we decided to install a new charged particle detector, DCV, inside the high vacuum region downstream of the electromagnetic calorimeter. To maximize detector acceptance, the DCV is placed as close as possible to the electromagnetic calorimeter. Since the DCV is able to support the membrane, we don't need the G10-pipe inside the CC04 anymore. The G10-pipe placed inside the calorimeter is still needed, however, its length can be shortened.

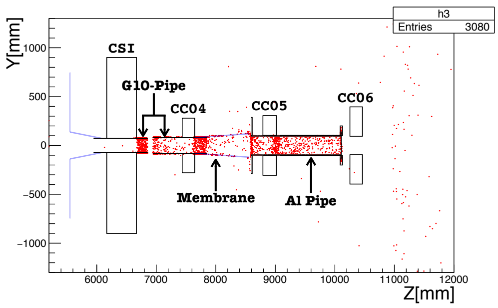


Figure 1. Interacting point of π^+ and π^-. Red dots indicate where the charged pions are disappeared.

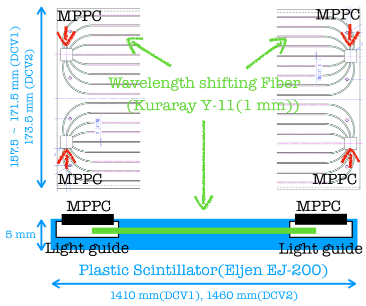


Figure 2. Configuration of scintillator with WLS fibers and MPPCs.

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, and the DCV2 is placed at 76 mm downstream from the DCV1 and inside the aluminum beam pipe. 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. A 1-mm-round wavelength shifting(WLS) fibers(Y11, Kuraray) is embedded in 18 parallel grooves in a 5-mm-thick plastic scintillator(EJ-200, Eljen Technology). Due to the limited space for the DCV, we need to attach the MPPCs on the scintillator surface directly. An aluminum light guide for the MPPCs is placed in both ends of the scintillator, and the WLS fibers are routed into the light guide. Since the size of the light guide is 6×6 mm^2 to fit the size of MPPC, the WLS fibers should be bent to converge into the light guide as shown in Fig. 2. The curvature of grooves near the end of scintillator is designed to be smaller than 20 mm in radius. The light loss increases rapidly below the radius of 20 mm, as illustrated 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).

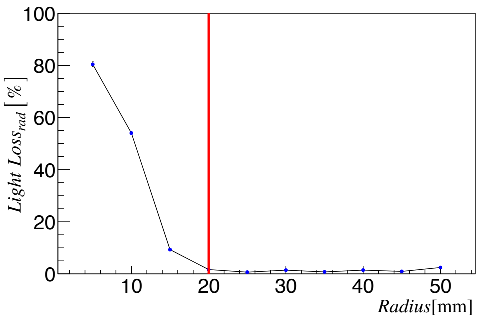


Figure 3. The light loss due to the curvature of the WLS fiber.

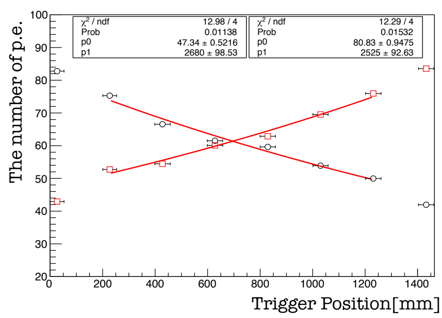


Figure 4. The number of p.e. at each cosmic-ray trigger point

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 placed 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.

Four MPPCs are attached to each side of the DCV scintillator and operated at a common high voltage. A MPPC gain was measured using a single photoelectron spectrum to group similar gain MPPCs.

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 60.2 for the DCV1 and 58.6 for the DCV2 according to energy deposit by cosmic-rays(0.8 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.

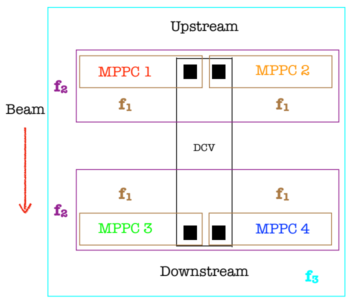


Figure 5. Three different gain factors for the DCV energy calibration with 4 MPPCs.

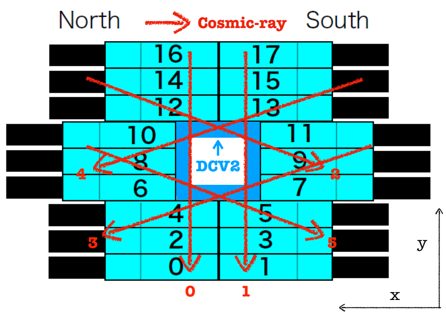
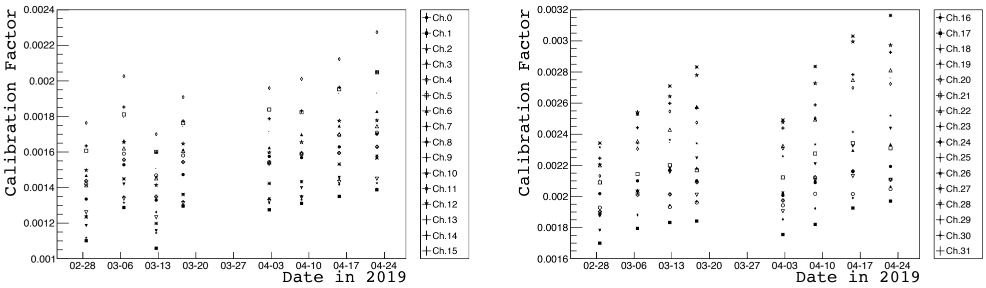


Figure 6. Tracks of the cosmic-rays identified by the CC05 for the DCV2 calibration.

4. Energy Calibration

After the installation of the DCV, 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 estimate an amount of energy deposit by the cosmic-ray in the DCV. Since the scintillation light was shared by 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 through only half parts of the DCV in which a clear peak in ADC distribution can be obtained at single MPPC. For example, track 1 was used to get ADC distribution for MPPCs placed at the south parts of the top and bottom plates. After fitting the Landau distribution convoluted with Gaussian to the obtained ADC distributions of each MPPC, we evaluated the gain factor f_1 for them individually. Secondly, we corrected the effect of shower sharing(f_2) by summing up calibrated ADC values with the f_1 for two MPPCs at both ends individually and fitted again the same function. Finally, we summed 4 calibrated ADC values applied the two factors(f_1 and f_2) at the same time and fitted again, and 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 undergoing.



(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, DCV, for further rejection of the background events from the $K_L \rightarrow \pi^+\pi^-\pi^0$ decay. Based on the cosmic-ray test performed during its fabrication, the light yield is about 60 photoelectrons for 0.8 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