Studies of optical fibre and SiPM readout system for the Cylindrical Trigger Hodoscope in COMET Phase-I

Yuki Fujii*[1], Masaharu Aoki[2], Sam Dekkers[1], Jordan Nash[1], Junji Tojo[3], Kazuki Ueno[2,4], and Hiroyuki Wakabayashi[2]

[1]School of Physics and Astronomy, Monash University, Clayton, Australia
[2]Department of Physics, Osaka University, Toyonaka, Japan
[3]Department of Physics, Kyushu University, Fukuoka, Japan
[4]Institute for Particle and Nuclear Studies, High Energy Accelerator Research Organization, Tsukuba, Japan

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Abstract

The COMET Phase-I experiment aims to search for a muon to electron (μ-e) conversion with 100 times better sensitivity than the current upper limit to investigate new physics scenarios. For COMET Phase-I, we have designed a primary trigger and timing detector called the Cylindrical Trigger Hodoscope (CTH), which consists of concentric double layer plastic scintillator rings. The detector must be operated within a high radiation environment of up to 10^{12} neutrons/cm^2 and 1 kGy gamma ray dose, therefore scintillation photons will be readout by optical fibres and detected by silicon photomultipliers (SiPMs) outside of the detector solenoid, where the radiation level is expected to be an order of magnitude lower. Here we report the estimated SiPM degradation from neutron irradiation tests, the timing resolution measured with a small counter test, and the light yield obtained in a full scale single counter measurement.

*Speaker yuki.fujii@monash.edu
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1 Introduction

The COMET experiment aims to search for μ-e conversion with a single event sensitivity of 3×10^{-15} in its Phase-I physics measurement at J-PARC (Japan Proton Accelerator Research Complex), Tokai, Japan [1]. The rate of μ-e conversion is extremely suppressed to be less than 10^{-54} in the Standard Model (SM) with a minimal extension to include neutrino oscillations. In contrast, its rate is expected to be significantly enhanced in many new physics models. If the μ-e conversion is discovered, it would therefore be clear evidence of new physics. In the COMET Phase-I experiment, we will construct a detector solenoid after a pion capture solenoid and 90 degree bent muon transport solenoid. Inside the detector solenoid under a 1 T magnetic field, a Cylindrical Detector (CyDet) system will be installed to detect signal-like electrons while avoiding the direct beam particles concentrating around the beam axis. The CyDet consists of a Cylindrical Drift Chamber (CDC), a Cylindrical Trigger Hodoscope (CTH) and a series of the muon stopping target discs. The CDC will reconstruct the electrons' trajectories with $\approx$200 keV/c resolution, while the CTH will measure the timing of electrons with a 1 ns timing precision [2]. In this paper, the design of the CTH will be described and the R&D results from two CTH prototyping tests will be presented.

2 The Cylindrical Trigger Hodoscope

Figure 1 shows the conceptual design of a section of the CTH. The overall CTH system is composed of two sets of two concentric rings of plastic scintillation counters (BC-408, Saint-Gobain crystal), located at both ends of the CDC along the beamline. Each ring has 64 rectangular counters overlapping each other with a tilted angle. By taking four-fold coincidence in the same set of counters, accidental coincidences and low momentum electrons will be highly suppressed. Due to the high radiation levels inside the detector solenoid, 1×10^{12} neutrons/cm^2 and 1 kGy gamma-rays for 150 day long data acquisition [3], it is hard to install any delicate electronic components including photo-sensors around the detector region. Therefore we decided to extract scintillation photons via bundled 5–8 m plastic (PMMA) based optical fibres and put SiPMs outside the solenoid, where lower radiation levels are expected with easier maintenance accessibility. From the simulation studies, the neutron dose level was found to be an order of magnitude lower outside of the detector solenoid. At this level, SiPMs are operational by cooling them lower than $-30\,^{\circ}$C as long as there are enough photoelectrons [4]. In order to evaluate the feasibility of the above design concept, a few small prototypes have been constructed and tested as reported in the following sections.

3 Test Measurements and Results

Two different measurements were performed in order to verify the conceptual design of the CTH, using a fast plastic scintillator together with a bundle of plastic optical fibres and SiPM.

3.1 Timing Measurement

A timing measurement was completed with a small prototype setup consisting of three small plastic scintillators arranged as shown in Figure 2 (a). In this setup, two small trigger counters were placed top and bottom of the main counter, orthogonally arranged to select the cosmic rays penetrating at the middle of the counter perpendicularly. Four SiPMs (Hamamatsu S14160-3015PS) were used in this timing measurement with three coupled directly to the scintillator counters and the fourth coupled to the other end of the main counter via a 9×1.0 m 1 mmϕ plastic fibre bundle. The top and bottom counters were used as trigger counters to identify the minimum ionisation particles (MIP) signal due to cosmic-rays. The timing of the two trigger counters was averaged and used as a reference time,t_{Ref}, and compared with the timing measured by the main counter's SiPMs. Applying a Gaussian fit to the distributions of signal times at the fibre end results in a measured time resolution of $\sigma = 1.0 \pm 0.1$ ns as shown in Figure 2 (b).

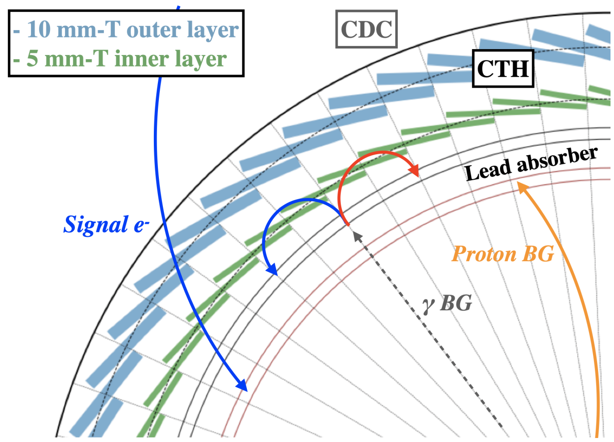

Figure 1: A conceptual design of a section of the CTH. Four-fold coincidence in the scintillator counters provides the main trigger condition in order to minimise background hits.

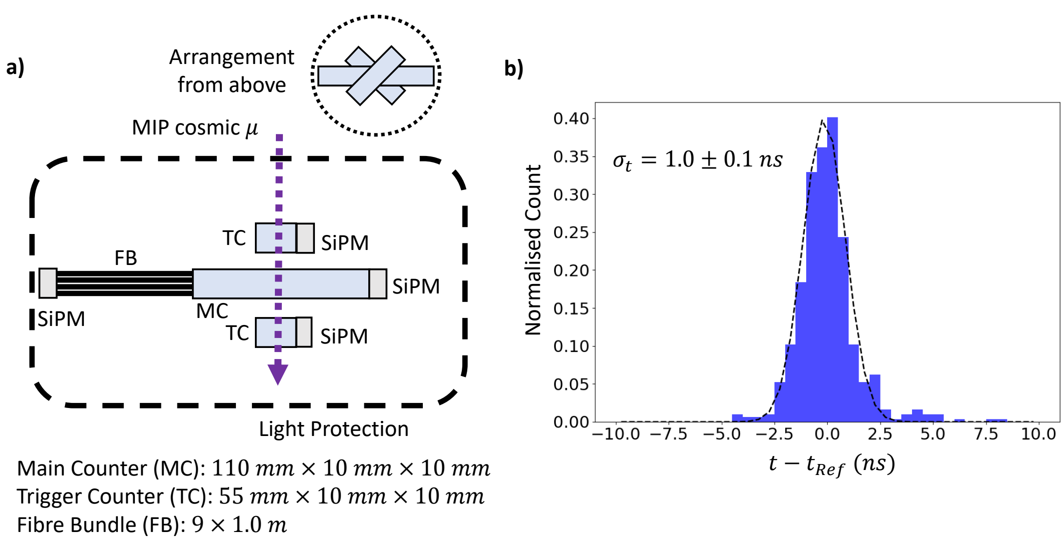

Figure 2: An experimental setup for a time resolution measurement (a) and the resulting timing distribution for the fibre coupled channel fitted with a Gaussian function (b).

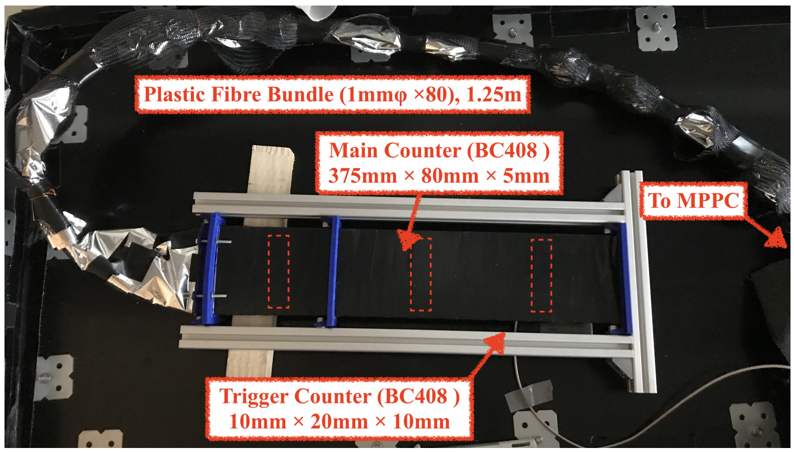

Figure 3: A picture of the light yield measurement setup with a full scale CTH inner counter and a small trigger counter.

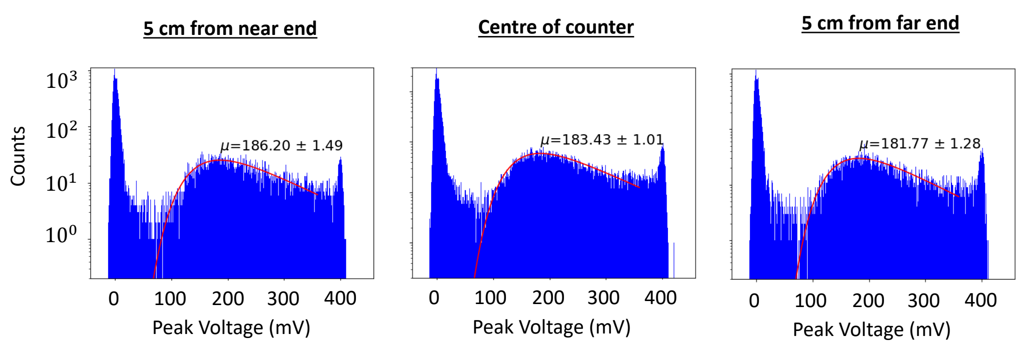

Figure 4: Peak voltage distributions from light yield measurements at three different trigger counter positions. A Landau function was fit to each distribution to extract mean peak voltage values.

3.2 Light Yield Measurement

A full scale CTH counter prototype was setup for a light yield measurement with $80 \times 350 \times 5\,\mathrm{mm}^3$ geometry, coupled to a SiPM (Hamamatsu S14161-3050-HS-04) via an $80 \times 1.25\,\mathrm{m}$ $1\,\mathrm{mm}\phi$ plastic fibre bundle that covers one end of the counter with about 15% geometrical coverage. A small counter was placed underneath to make a trigger for MIP signals. The trigger counter was placed at three different positions to measure the longitudinal dependence in the photon detection efficiency. The triggered waveforms were collected and a histogram of accumulated waveform peaks was fitted with a Landau distribution to extract the mean pek voltage value as shown in Figure 4. The results show greater than 40 photoelectrons detected in each of the three positions scanned based on a measured single photoelectron peak size of 4.2 ± 0.1 mV, also showing no strong positional dependence along the counter.

4 Summary

In COMET Phase-I, the CTH detector will measure the timing of signal-like electrons with 1 ns resolution and make a primary trigger signal under high radiation and high hit rate conditions. To operate within such a harsh environment, a clear plastic fibre bundle to SiPM readout scheme was chosen. The neutron irradiation test clarified the expected performance degradation in SiPMs under 1×10^{11} neutrons/cm^2, making a cooling system mandatory as well as setting a minimum photoelectron requirement for signals; we require greater than 20 p.e. for MIP signals. A cooling system is now being developed to achieve a temperature below $-30\,^{\circ}\mathrm{C}$ around the SiPMs to compensate for the increase in dark current due to the radiation damage. A timing resolution of 1 ns was obtained with a small counter and fibre read-out system for MIP signals from cosmic-rays. With an actual scale prototype, we obtained greater than 40 photoelectrons for a 5mm-thick counter without strong positional dependence. This number of photons is large enough to achieve the target timing resolution and radiation tolerance. From those results, we concluded the CTH design is feasible and more detailed detector responses will be studied with a 100 MeV electron beam in near future.

References

[1] G. Adamov *et.al.* (COMET Collaboration), Progress of Theoretical and Experimental Physics 2020, 033C01 (2020) 10.1093/ptep/ptz125.

[2] Y. Fujii, Proceedings of the 3rd J-PARC Symposium (J-PARC2019), doi: 10.7566/JPSCP.33.011109.

[3] S. Dekkers *et.al.*, IEEE Transactions on Nuclear Science, **68**, 8, pp. 2020–2027, 2021, doi: 10.1109/TNS.2021.3084961.

[4] A. Comerma, 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2017, pp. 1–6, doi: 10.1109/NSSMIC.2017.8532796.