PROCEEDINGS OF SCIENCE

Development of the Online System for COMET Phase-I

Chihiro Yamada,[a,*] **Sanshiro Enomoto,**[b] **Yuki Fujii,**[c] **Yoichi Igarashi,**[d] **Yuto Kageyama,**[a] **MyeongJae Lee,**[e] **Masaki Miyataki,**[a] **Satoshi Mihara,**[d] **Ryo Nagai,**[a] **Takuho Nakabayashi,**[f] **Yu Nakazawa,**[d] **Kou Oishi,**[c,d] **Masayoshi Shoji,**[d] **Siyuan Sun,**[a] **Syunya Ueda**[a] **and Kazuki Ueno**[a]

[a] *Department of Physics, The University of Osaka, Toyonaka, Osaka 560-0043, Japan*

[b] *Department of Physics, University of Washington, Seattle, WA 98195, USA*

[c] *Department of Physics, Imperial College London, London SW7 2BW, United Kingdom*

[d] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*

[e] *Department of Physics, Sungkyunkwan University, Suwon, Gyeonggi-do 16419, Republic of Korea*

[f] *Department of Particle and Nuclear Physics, SOKENDAI, Tsukuba, Ibaraki 305-0801, Japan*

E-mail: c-yamada@epp.phys.sci.osaka-u.ac.jp, sanshiro@uw.edu, y.fujii@imperial.ac.uk, Youichi.Igarashi@kek.jp, y-kageyama@epp.phys.sci.osaka-u.ac.jp, m-miyataki@epp.phys.sci.osaka-u.ac.jp, satoshi.mihara@kek.jp, rnagai@epp.phys.sci.osaka-u.ac.jp, takuho@post.kek.jp, yu.nakazawa@kek.jp, kou.oishi@kek.jp, mshoji@post.kek.jp, sun-yuan@epp.phys.sci.osaka-u.ac.jp, s-ueda@epp.phys.sci.osaka-u.ac.jp, kazuueno@phys.sci.osaka-u.ac.jp

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)568

The COMET Phase-I experiment aims to search for the muon-to-electron conversion process with a target single event sensitivity of 3×10^{-15}. The main detector, consisting of Cylindrical Drift Chamber (CDC) and Cylindrical Trigger Hodoscope (CTH), requires an online system capable of high-rate, low-latency operation, while also being sufficiently flexible and robust. This contribution reports on the development status of the online system, including the scalable asynchronous data acquisition framework, the integrated slow control system, and the multi-stage hardware trigger system. We also present the results of full hardware integration tests for the CDC trigger system, focusing on communication stability over long-distance connections with DisplayPort cables and end-to-end trigger latency measurements. The system operated for about 18 hours without communication errors, and the total trigger latency is confirmed to satisfy the 8.5 μs requirement.

The European Physical Society Conference on High Energy Physics (EPS-HEP 2025)
7–11 July 2025
Marseille, France

1. Introduction

The COMET (COherent Muon to Electron Transition) experiment [1], currently under construction at J-PARC, aims to search for the neutrinoless muon-to-electron conversion process $\mu^- N \rightarrow e^- N$ in aluminium, a charged lepton flavour violation process. Phase-I is designed to reach a single-event sensitivity of 3×10^{-15} over 150 measurement days, improving the SINDRUM-II limit obtained with a gold target by two orders of magnitude [2]. The experiment uses a high-intensity pulsed proton beam. The beamline shown in figure 1, employs a series of superconducting solenoids to capture pions produced at the production target and transport the resulting muons to an aluminium stopping target. Conversion electrons with a mono-energy of 105 MeV are identified by the main detector, CyDet (Cylindrical Detector), through the measurement of their tracks in a 1 T magnetic field.

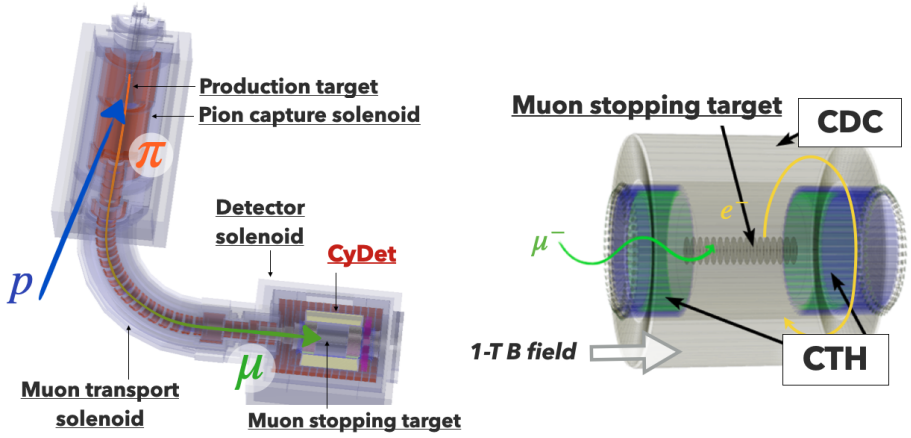

Figure 1: Schematics of the COMET Phase-I beamline (left) and design of the CyDet (right). Aluminium disks at the centre act as the muon stopping target, and signal electrons are measured by the CDC and CTH inside a 1 T magnetic field.

CyDet consists of two subdetectors, as shown on the right side of figure 1: Cylindrical Drift Chamber (CDC) [3] and Cylindrical Trigger Hodoscope (CTH). CDC provides momentum reconstruction with a resolution of 200 keV/c. It contains 4,986 sense wires arranged in 20 radial layers and filled with a He–iC_4H_{10} (90:10) gas mixture. CTH consists of 64 plastic scintillation counters, which detect the signal timing with a resolution of 1 ns. They are placed upstream and downstream inside the CDC, and each CTH comprises two circular layers arranged with a half-overlapping geometry. A signal electron passes through four counters, and a primary trigger is issued when the associated counters record coincident hits.

To fully exploit the performance of CyDet and achieve the required sensitivity, a sophisticated online system is essential. The intense pulsed proton beam produces a substantial background and high radiation level environment. To cope with these conditions, COMET Phase-I requires a robust online system capable of high-rate data handling, low-latency trigger generation, and stable long-term operation. The design and performance of the online system are presented in the next section.

2. Online System

To meet the physics goals of COMET Phase-I, the online system must satisfy several operational requirements. First, it must cope with high-rate operation, as the primary trigger rate from the CTH is expected to reach approximately 200 kHz. The electronics installed in the detector area must also maintain stable detector performance in a high-radiation environment, with expected exposures of up to 10^{12} n/cm^2 and about 1 kGy, including a safety factor. In addition, the total trigger latency must remain below 8.5 μs, imposed by the buffer size of the readout electronics. Efficient signal selection is essential for achieving the target single-event sensitivity. Specifically, the online trigger must select over 90% of conversion electron candidates. Finally, long-term operational stability is essential, with minimal dead time and the capability for rapid recovery from errors such as communication failures or link instabilities.

These requirements are addressed by a modern modular online system consisting of a scalable data handling and data acquisition (DAQ) system, a monitor system with stable management of detectors and devices, and a multi-stage hardware trigger system.

2.1 Data Acquisition System

The DAQ system is built on the NestDAQ framework [4, 5], which provides a parallel and fully asynchronous software architecture for managing data taking. As shown in figure 2, each stage of the DAQ chain, consisting of front-end electronics, sampler processes, event builders, and data recorders, is implemented as an independent, distributed processing unit. In this architecture, each processing unit operates concurrently with the others, communicating through a unified DAQ network. This parallelism is crucial for handling the high event rates expected in COMET Phase-I.

The achievable DAQ throughput is determined by the bandwidth limitations of the hardware interfaces. Each front-end electronics module can transmit data at up to 1 Gbps, and the bandwidth of the online data-storage server imposes an overall limit of about 10 Gbps on the total recording rate. Consequently, the maximum sustainable DAQ throughput is primarily constrained by this backend storage bandwidth. The system also allows for an optional software trigger stage, in which additional event filtering can be performed to reduce the load on the event builders. A full CDC DAQ test using a single event-builder node demonstrated a sustained throughput of 650 MB/s, confirming that NestDAQ can be used for Phase-I operation.

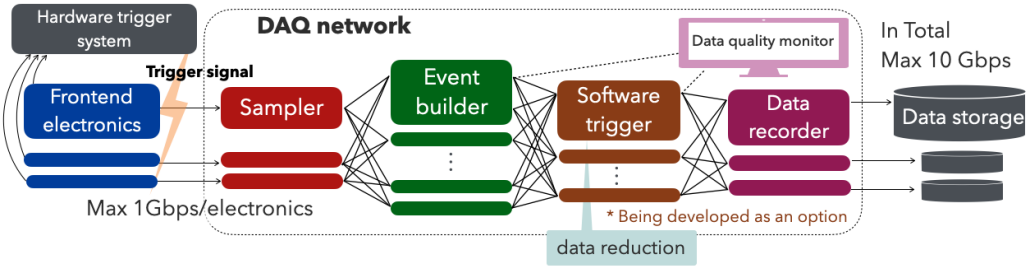

Figure 2: Design of DAQ system. Data flow proceeds from left to right. The DAQ network is where the distributed components operate asynchronously and in parallel through interconnected processing pipelines.

2.2 Monitor System

The online monitor system is designed to be scalable and user-friendly. The front-end layer interacts directly with individual devices and can be developed independently of the higher-level framework. The middle layer manages data exchange, including communication via a unified protocol, database handling, and raw-data storage. The user backend layer is implemented using the SlowDash framework [6], which provides a unified web-based user interface.

SlowDash supports a wide range of modern databases and communication protocols and offers live visualisation of detector conditions. For the CDC, SlowDash has been used to develop real-time hit-map displays for both accumulated and event-by-event views. These displays have already been employed during cosmic-ray test runs, demonstrating the responsiveness and practicality of the monitor system in realistic operation.

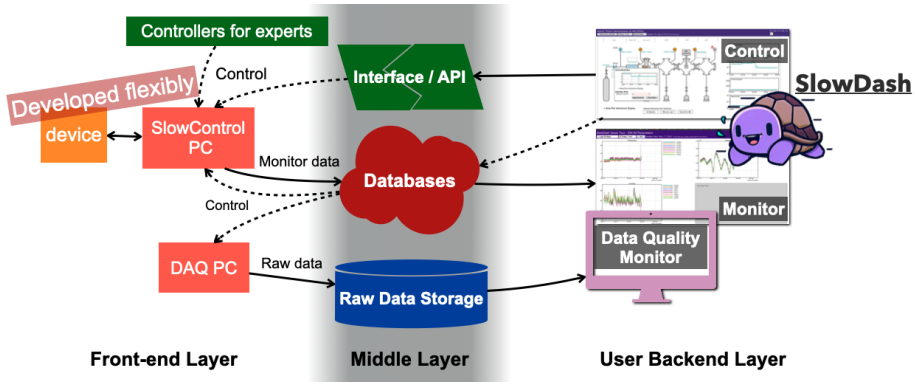

Figure 3: The concept design of slow control system

2.3 Trigger System

The trigger system of COMET Phase-I is designed to perform fast and efficient online event selection by combining information from both the CDC and the CTH. It is implemented using a two-stage hardware architecture called COTTRI (COmeT TRIgger) [7]. Figure 4 shows the block diagram of the CyDet trigger system. Signals from the CDC are digitised by the readout board called RECBE, which is developed by adapting the readout electronics of the Belle II Central Drift Chamber [8]. The digitised waveforms are sent to the COTTRI CDC Front-End (FE) boards, which perform wire-by-wire scoring [9]. The COTTRI CDC Merger Board (MB) then receives these scores from COTTRI CDC FEs and processes event classification to generate trigger candidates [10]. The CTH signals are processed in a parallel chain by the COTTRI CTH FE and the COTTRI CTH MB, where coincidence-based trigger processing is carried out.

Trigger candidates from each MB are collected by the Central Trigger module, FC7 developed at CERN [11], which integrates the inputs and issues a global trigger. The trigger is then distributed back to the RECBEs through the Fast Control & Trigger (FCT) system, ensuring synchronous readout.

The FC7 also provides the master clock for the entire system by using the accelerator clock as its reference, and distributes both clock and trigger signals to external systems, such as the

cosmic-ray veto, which rejects background from cosmic muons, and the muonic X-ray monitor, which measures the stopping muon rate.

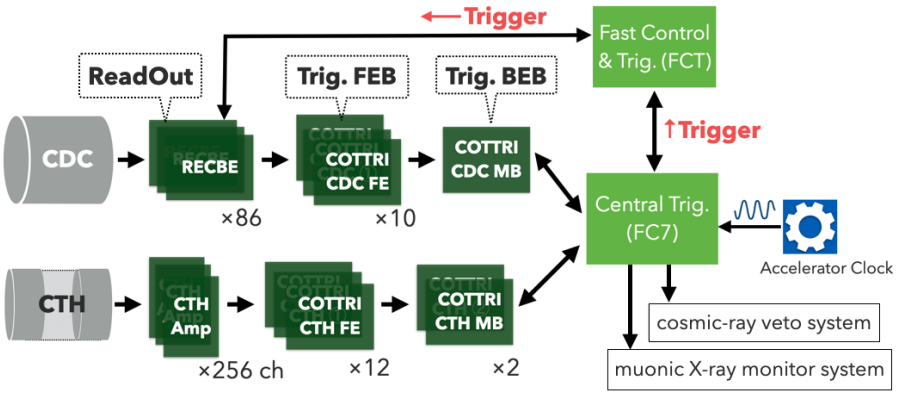

Figure 4: Block diagram of CyDet Trigger system.

Communication among the electronics boards is performed using the Aurora 8B/10B protocol [12]. Links between the COTTRI CDC (CTH) FE, COTTRI CDC (CTH) MB, and the RECBE use copper DisplayPort (DP) cables. Optical communication cannot be used in this region because the RECBEs are located in the detector area, where high gamma-ray radiation doses may damage optical transceiver modules. In particular, the connection between the RECBE and the COTTRI CDC FE requires a cable length of approximately 5 m to place the COTTRI CDC FE outside the high-radiation area.

To ensure stable operation under these conditions, the FPGA firmware continuously monitors the communication status. The system checks the Aurora link-up status, 8B/10B code errors, and the internal Error Correction Code (ECC), which identifies single-bit and double-bit errors in the received data. Single-bit errors are automatically corrected, while double-bit errors are unrecoverable. All detected errors are recorded in internal registers and read out by the online monitor system to assess the communication stability.

3. Full-chain CDC Trigger Test

If communication between electronics fails, the CDC trigger cannot be issued correctly. The system first attempts an automatic reset of the communication module, however, if this fails, the FPGA firmware must be reconfigured, resulting in a few minutes of DAQ dead time. Therefore, it is essential to evaluate the communication stability under conditions as close as possible to the actual experimental environment.

For this purpose, a full-chain hardware test was carried out, connecting the CDC and all CDC trigger components: 86 RECBEs, 10 COTTRI CDC FEs, 1 COTTRI CDC MB, 7 FCTs with distributors, and 1 FC7 module. The setup is shown in figure 5. A 12 MHz clock generated by a function generator (FG) was supplied to the FC7, and communication errors were continuously monitored throughout the test. During a total run time of 6.7×10^4 s, no communication errors were observed. The resulting 95% C.L. upper limit on the error rate is 4.6×10^{-5} s^{-1}, corresponding to

a DAQ live time of more than 99% under the assumption that each communication failure would require a recovery time of three minutes.

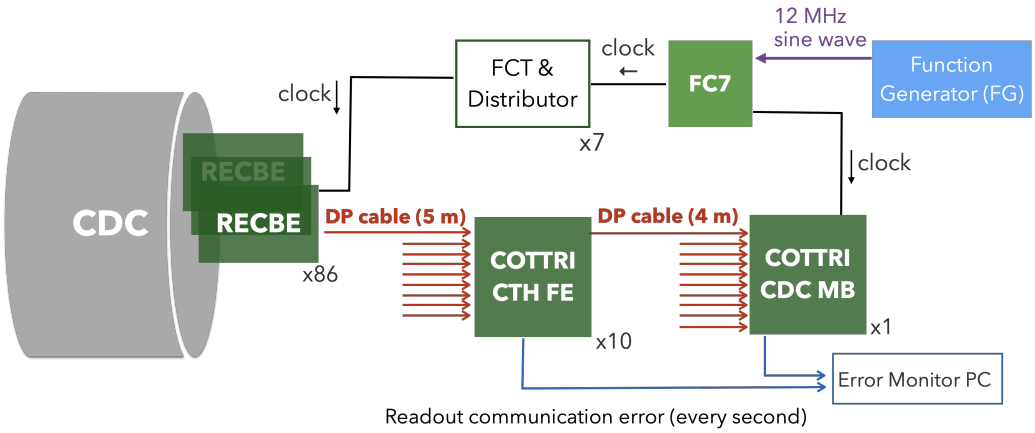

Figure 5: Block diagram of the communication stability measurement setup.

After establishing the long-term communication stability of the CDC trigger chain, we next evaluated the end-to-end trigger latency. As noted earlier, the total latency must remain within 8.5 μs, and verifying this timing performance is essential.

To assess this, the end-to-end latency of the CDC trigger chain was evaluated by injecting a test pulse into the RECBE and measuring the timing at each stage of the system. Figure 6 shows the block diagram of the latency measurement chain and an oscilloscope capture of the signals corresponding to the major processing steps. After the test pulse is applied, the CDC charge extraction and hit scoring performed in the COTTRI CDC FE appear at 1.0–1.1 μs. The 0.1 μs spread in this timing is primarily due to the 10 MHz sampling rate of the data used for the trigger logic, which limits the timing granularity of the RECBE-to-FE processing. The CDC trigger generated in the COTTRI CDC MB follows at around 1.5–1.6 μs, after which the trigger information is sent through the FCT path, reaching the central trigger processing stage at 2.2–2.3 μs. Finally, the global trigger signal returns to the RECBE at 3.0–3.1 μs. Combining these contributions, the total latency of the trigger system is measured to be 3.4–3.5 μs, comfortably satisfying the 8.5 μs requirement.

4. Conclusion

The COMET experiment aims to search for the charged lepton flavour violation process of muon-to-electron conversion using the high-intensity pulsed proton beam at J-PARC. As part of the preparations for COMET Phase-I, we have developed the online system comprising the data acquisition, slow control, and hardware trigger systems, and have evaluated its performance with the full CDC trigger chain. The Aurora links operated over 5 m DP cables demonstrated stable performance, with no errors observed over an 18-hour test. The result of the latency measurement also confirmed that the trigger chain satisfies the 8.5 μs requirement. These results demonstrate that the online system has reached the reliability and performance needed for efficient data taking in COMET Phase-I. Future work includes completing the integration of the CDC and CTH trigger systems in preparation for beam-based commissioning.

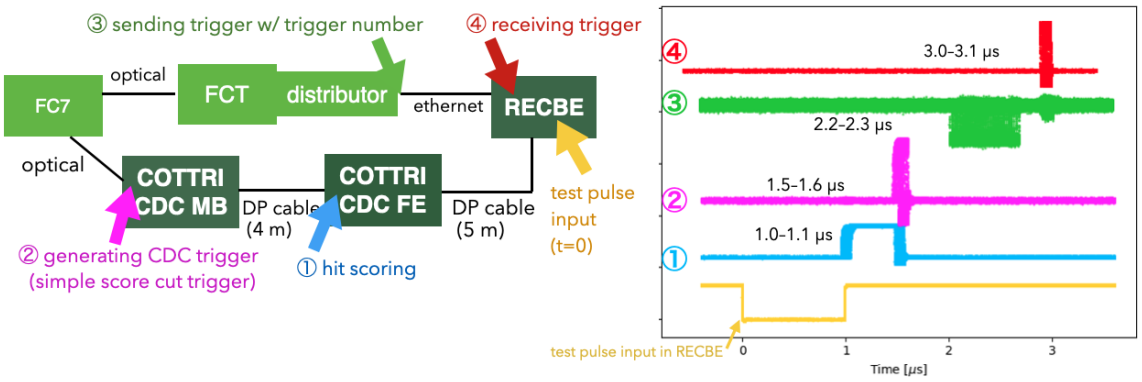

Figure 6: Oscilloscope traces used for the end-to-end latency measurement of the CDC trigger chain. A test pulse injected into the RECBE (yellow) initiates the sequence. The CDC hit scoring signal from the COTTRI CDC FE appears at 1.0–1.1 μs (blue), followed by the CDC trigger generation in the COTTRI CDC MB at 1.5–1.6 μs (magenta). The trigger transmission through the FCT is observed at 2.2–2.3 μs (green), and the final trigger reception in the RECBE occurs at 3.0–3.1 μs (red).

References

[1] R. Abramishvili *et al.* (2020), *COMET Phase-I Technical Design Report*, *Prog. Theor. Exp. Phys.* **2020**, pp.102, 033C01[hep-ex/1812.09018]

[2] W. Bertl *et al.* (2006), *A search for μ-e conversion in muonic gold*, *Eur. Phys. J. C* **47** pp.337–346

[3] A. Sato *et al.* (2024), *Design and construction of the cylindrical drift chamber for the COMET Phase-I experiment*, *Nucl. Instrum. Meth. A* **1069** 169926

[4] T. Takahashi *et al.* (2023), *Streaming DAQ Software Prototype at the J-PARC Hadron Experimental Facility*, *IEEE Trans. Nucl. Sci.* **70**, no.6, pp.922–927

[5] Y. Igarashi *et al.* (2024), *Implementations of Streaming DAQ on Actual Detector Systems*, *IEEE Trans. Nucl. Sci.* **72**, no.3, pp.421–428

[6] S. Enomoto, https://github.com/slowproj/slowdash

[7] Y. Fujii *et al.* (2018), *Development of the Fast Front-end Trigger System for COMET Phase-I*, *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)*, Sydney, NSW, Australia, 10–17 November 2018; pp.1–4

[8] T. Uchida *et al.* (2011), *Readout electronics for the central drift chamber of the Belle II detector*, *2011 IEEE Nuclear Science Symposium Conference Record, Valencia, Spain, 2011, pp. 694-698*

[9] Y. Nakazawa *et al.* (2021), *An FPGA-Based Trigger System With Online Track Recognition in COMET Phase-I*, *IEEE Trans. Nucl. Sci.* **68**, no.8, pp.2028–2034[physics.ins-det/2010.16203]

[10] M. Miyataki *et al.* (2024), *Neural network based event selection on FPGA for COMET Phase-I*, *2024 IEEE Nuclear Science Symposium (NSS), Medical Imaging Conference (MIC) and Room Temperature Semiconductor Detector Conference (RTSD)* , Tampa, FL, USA, 2024, pp. 1–1

[11] M. Pesaresi *et al.* (2015), *The FC7 AMC for generic DAQ & control applications in CMS*, *JINST* **10**, C03036

[12] AMD Inc., (2012), *LogiCORE IP Aurora 8B/10B v5.3 User Guide (UG353)*, https://docs.amd.com/v/u/en-US/aurora_8b10b_ug353