# Development of a scintillating-fiber-based beam monitor for the Coherent Muon-to-Electron Transition experiment

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## Abstract

COMET is a leading experiment to search for coherent conversion of $ mu^- mathrm{N} to e^- mathrm{N}$ with a high-intensity pulsed muon beamline, produced by the innovative slow extraction techniques. Therefore, it is critical to measure the characteristics of the muon beam. We set up a Muon Beam Monitor (MBM), where scintillation fibers (SciFi) weaved in the cross shape are coupled to silicon photomultipliers (SiPM), to measure the spatial profile and timing structure of the extracted muon beam for COMET. The MBM detector has been tested successfully with a proton beamline in China Spallation Neutron Source (CSNS) and taken data with good performance in the commissioning run called COMET Phase-$ alpha$. Experience of the MBM development, such as the mechanical structure and electronics readout, and its beam measurement results will be shared.

## Full Text

## Preamble

### Development of a SciFi-based beam monitor for COMET

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COMET is a leading experiment to search for coherent conversion of $\mu^- N \rightarrow e^- N$ with a high-intensity pulsed muon beamline, produced by innovative slow extraction techniques. Therefore, it is critical to measure the characteristics of the muon beam. We have developed a Muon Beam Monitor (MBM) featuring scintillation fibers (SciFi) woven in a cross-shaped configuration and coupled to silicon photomultipliers (SiPM) to measure the spatial profile and timing structure of the extracted muon beam for COMET. The MBM detector has been successfully tested with a proton beamline at the China Spallation Neutron Source (CSNS) and demonstrated good performance during data taking in the commissioning run known as COMET Phase-$\alpha$. This paper shares our experience in developing the MBM, including its mechanical structure and electronics readout, along with beam measurement results.

**Keywords:** Beam Instrumentation, Profile Monitor, Scintillation Fiber, Silicon Photomultipliers

## Introduction

As beam power and intensity requirements for high-precision measurements in particle and nuclear physics continue to grow, beam profile monitors have become essential for precisely characterizing beam properties [1-3], particularly for real-time beam control. Such monitors must provide fast response, high time resolution, and quasi-non-invasive operation.

Several types of beam profile monitors are currently in use. The most widely employed are Beam Position Monitors (BPMs), which detect the transverse beam position by measuring voltage differences between opposite pick-ups [4]. BPMs come in various configurations, including button BPMs for the Chinese initiative Accelerator Driven Sub-critical system [5], cavity BPMs for the International Linear Collider (ILC) [6], and stripline BPMs in the KEKB injector linac [7]. Another important category comprises gas-based detection systems, typically utilizing gas sheets [8]. Due to their excellent stability and non-invasive nature, gas detectors are widely used for online beam profile measurements, such as for 400 MeV negative hydrogen atoms in the J-PARC LINAC [9–11], muon beam measurements in the NOvA experiment at Fermilab [12], and electron/proton beam measurements in the High Luminosity LHC [13]. A third approach uses multichannel plates (MCP) [14, 15] with optical readout, applied in the muon g-2 experiment [16–18] and planned for operation at CSNS [19] and HIRFL-CSR [20]. MCP detectors operate by amplifying avalanches triggered when injected electrons strike the MCP, with signals recorded by an anode collector board. This design enables measurement of high-intensity beams, tolerating rates up to $10^6$ μ/s [17].

For individual particle measurement, scintillation fiber detectors offer an excellent solution [21] due to their high light yield and fast response, typically coupled to SiPMs for photon detection [22]. Such beam profile monitors have been employed in the R484/R582 experiments at RIKEN [23] and the MEG-II experiment at PSI [24]. Scintillation fiber detectors can measure hit times with accuracies of O(1) ns and determine deposited energy through photoelectron counting. These high-precision capabilities also enable charged particle identification when combined with multiple detection systems [25].

The COMET (COherent Muon to Electron Transition, J-PARC E21) experiment is a next-generation, world-leading search for charged lepton flavor violation (cLFV) via the coherent neutrinoless muon-to-electron conversion ($\mu^- \to e^-$ conversion) process [26]. COMET aims to achieve a single-event sensitivity (S.E.S.) of $2.7 \times 10^{-17}$, four orders of magnitude better than the current limit set by SINDRUM-II [27]. An 8 GeV bunched proton beam with 1 MHz pulse structure is slowly extracted from the J-PARC main ring (MR) [28–30] and strikes a stopping target to generate the required muon beam. A key aspect of the experiment is high-precision measurement of the COMET muon beam, necessitating beam monitoring during commissioning [31].

We have designed a muon beam monitor to measure and characterize the COMET muon beam. The goal was to create a simple, cost-effective detector with compact size and low power consumption that could operate reliably in high-radiation environments. This article reviews the detector' s structure and performance, presents test results with high-intensity proton beams, and describes its performance during the COMET Phase-$\alpha$ commissioning.

## II. Detector System

### A. Mechanical Structure

The core of the MBM is a grid of multi-clad square 1-mm-wide SCSF-3HF scintillation fibers produced by Kuraray [32, 33], coupled at one end to S13360-1350PE SiPMs from Hamamatsu [34]. The fibers form a square beam window arranged along X and Y axes, with the orthogonal axes perpendicular to the beamline direction. The selected SiPM has an effective photosensitive area of $1.3 \times 1.3$ mm$^2$, matching the fiber cross-section, and the spectral responses of the scintillation fiber and SiPM are well-matched to minimize photon loss at the interface. Square fibers make the detector response independent of the muon trajectory position within a fiber and minimize dead space. The fibers are cut and polished with a diamond tool, and silicone grease is applied at the contact end to improve photon transport efficiency through the fiber-SiPM interface. The fibers are divided into two perpendicular layers spaced 0.8 mm apart, covering a $30 \times 30$ cm$^2$ beam window. Each layer contains 128 fibers, 500 mm long with 1.3 mm spacing, enabling beam profile measurement in two orthogonal directions (X+Y).

[Figure 1: see original paper] The setup of the MBM structure

Scintillation fibers feature a total internal reflection cladding structure that achieves extremely high light collection efficiency and improves detector efficiency. When charged particles traverse a scintillation fiber, they lose energy through ionization. This energy loss can be estimated using the Bethe-Bloch formula [35]. For organic scintillator materials with density near 1 g/cm$^3$, the minimum ionizing energy loss dE/dx is approximately 200 keV/mm [36], which is acceptable for high-intensity muon beams at O(10) MeV energies. The mesh structure further reduces average energy loss, enabling quasi-non-invasive operation. Through this quasi-non-invasive design and pure geometric calculations, we estimate that 60% of muons passing through the beam window will be recorded, while 16% will trigger both layers and produce coincident signals. These signals provide hit maps of muons and enable beam profile characterization.

All scintillation fibers and their modules are mounted on an aluminum plate, with the fiber grid shielded in a stainless steel box for light protection. The beam window location on the stainless steel box is cut out and covered with two layers of 50 µm-thick aluminum foil. In addition to the fiber grid, the electronic system is installed on the aluminum plate, comprising two electronic modules and one Time Logic Unit (TLU). The electronic modules are mounted on opposite sides of the detector with SiPMs coupled to fiber ends, while the TLU module is positioned at a corner of the Al plate for convenient communication with electronics on both sides. All electronic boards are enclosed in resin shells with metal surface layers to prevent dust and reduce occasional single-particle flip damage from beam particle scattering. The complete MBM assembly is shown in Fig. 1.

### B. Electronics Readout

The MBM electronics readout consists of two main components: two electronic modules that read out signals and upload data to the host computer, and one TLU that synchronizes the clock timing between the two electronic modules. Each electronic module contains three parts: SiPM Carrier, Frontend Electronics Board (FEB), and Data Acquisition (DAQ) Board.

The SiPM Carrier holds 128 SiPMs arranged in a 16 × 8 array and connects to the FEB via an edge connector. The SiPM converts photons to photoelectrons, forming a current signal that is integrated by a charge-sensitive preamplifier to produce a pulse signal with fixed time length and 3.3 V amplitude for processing by the FEB. A power-supply module on the SiPM carrier ensures stable power to all 128 channels and features a built-in temperature compensation system that adjusts voltage according to external temperature, improving SiPM stability across different environments.

The FEB primarily comprises two Application-Specific Integrated Circuit (ASIC) chips [37] and one Field Programmable Gate Array (FPGA). Each ASIC chip has 64 channels, each containing a charge-sensitive preamplifier, CR-RC shaping circuit, screener, and other modules. The ASIC chip amplifies signals and transmits them to the FPGA while maintaining real-time connection to the TLU through HDMI. The TLU sends a clock and sampling start signal to the FEB, combining it with a timestamp generated at approximately 1 Hz by threshold calibration. This approach ensures high signal-to-noise ratio during beam monitoring runs.

Due to ASIC chip limitations, the electronics system can only record timing information from triggered signals, leaving charge information unrecorded. Fortunately, counting and recording threshold-crossing signals suffices for measuring beam profile and time structure. However, since SiPM characteristics such as dark rate and quantum efficiency vary significantly, the 256 MBM channels would exhibit diverse responses, degrading detector performance. We therefore carefully designed the electronics readout configuration to allow individual channel threshold adjustment, enabling uniform response across all channels. For each channel, we maintain the dark counting rate at approximately 1 Hz by calibrating the threshold, which we expect to yield high signal-to-noise ratio during beam monitoring.

### C. Validation of Detector Response

Following MBM assembly, we validated the detector' s operational status before beamline installation by continuously recording cosmic ray data for approximately three hours. This test addressed two questions: first, whether the detector could operate properly throughout the entire period; and second, whether it could record charged particles (cosmic muons) with high efficiency when compared to rough estimates.

For the first objective, we monitored the detector' s long-term operational status and observed stable data taking without interruption, as demonstrated by the trigger rate during this period in Fig. 2(a). For the second objective, we analyzed the recorded data and compared them with expectations. The cosmic ray muon flux at sea level is approximately $1/\mathrm{min/cm}^2$ [38], so we expected roughly 3 Hz in the MBM. With appropriate threshold settings, the dark count rate was reduced to 1 Hz per channel, resulting in an overall MBM trigger rate of O(100) Hz−about two orders of magnitude higher than the naive cosmic ray expectation. In this case, we switched to coincident measurement to collect cosmic ray muon events by requiring X and Y layer triggers within 20 ns, corresponding to $3\sigma$ of the fiber decay time. Based on a 20 ns coincidence window, the accidental coincidence rate from dark noise in two orthogonal scintillation fibers is $6.6 \times 10^{-4}$ Hz, much lower than the 2.8 Hz muon rate from Monte Carlo simulations. This dark noise frequency is therefore acceptable.

The results, shown in Fig. 2, are satisfactory. Fig. 2(a) shows a coincidence-triggered rate of approximately 3 Hz, consistent with expectations. The stable event rate in the plot indicates reliable long-term detector operation. Additionally, the nearly uniform detector response demonstrates good performance across all MBM channels (see Fig. 2(b)). Based on these observations, we conclude that MBM can operate stably for extended periods and possesses the required functionality to achieve physics objectives.

## III. Beam Tests

### A. Proton Beam Test at CSNS

To understand the detector response under high-intensity beams, we conducted a beam test at the Associated Proton beam Experiment Platform (APEP) at the China Spallation Neutron Source (CSNS) on January 9, 2023 [39]. The detector was installed on a movable bracket enabling precise X-Y positioning. Before testing, we used a laser collimator to align the beam window with the beam center.

For the APEP setup, the extracted proton beam had a 25 Hz repetition rate with 400 µs pulse length per bunch. A suite of degraders downstream of the proton beam window (PBW) allowed proton energy adjustment from 10 to 80 MeV. A collimation system enabled continuous tuning of uniform beam spot sizes from 10 mm × 10 mm to 50 mm × 50 mm at both vacuum and air test points. However, atmospheric scattering significantly increased the actual beam spot size in non-vacuum environments; for example, a 10 mm × 10 mm collimation setting produced approximately a 70 mm × 70 mm beam spot at the air test point [39].

[Figure 3: see original paper] Beam test results with high-intensity 80 MeV proton beam at CSNS. Panel (a) presents the timing structure of the proton beam in CSNS. Panel (b) shows the beam spot during CSNS beam tests.

The beam test served two purposes. First, we validated MBM' s ability to record beam time structure. Given the 25 Hz repetition rate, we selected data within 280 ms encompassing 8 pulses. The time structure shown in Fig. 3(a) exhibits clear regular peaks every 40 ms, consistent with the 25 Hz beam rate. Second, we validated the detector' s ability to measure beam profile by generating 2-D plots from X-Y coincidence events. However, during testing we observed serious radiation effects in some scintillation fibers operating in the 80 MeV proton beam for extended periods, with nearly all channels triggering continuously at ultra-high rates, particularly at previously scanned points. This severely polluted true proton events with radiation backgrounds. We therefore applied strict cuts to obtain clean signals: - Events must trigger within 10 ns on both X and Y layers - Trigger times must fall within the beam spill window

With these cuts, we obtained the result shown in Fig. 3(b), revealing a clear beam spot at the top center—exactly at the beam location. The beam spot size is approximately 70 mm × 70 mm, consistent with CSNS simulation results [39]. These tests confirm that MBM responds well to beam particles and can accurately record both beam timing structure and profile characteristics.

### B. COMET Phase-$\alpha$

To measure proton beam characteristics and $\pi/\mu$ production with minimal ambiguity—essential for the COMET experiment—the collaboration proposed a low-intensity beam run called Phase-$\alpha$ commissioning. A key objective was monitoring and measuring muon beam properties. The Phase-$\alpha$ detector system comprises four sub-detectors: MBM, Straw Tube Tracker, Range Counter (RC), and Proton Beam Monitor (PBM). As the first detector downstream of the muon beam, MBM monitors the timing structure and position information of the muon beam, providing a reference for downstream detectors and beamline quality. The Straw Tube Tracker, installed after MBM, measures particle position and direction [40]. Since this tracker is part of the COMET Phase-I detection system, Phase-$\alpha$ commissioning validates its performance in the beam environment, particularly its electronics. The Range Counter detector, consisting of plastic scintillators coupled to photomultiplier tubes (PMT), measures deposited energy and hit time of muon events. Its electronics can record approximately 10 µs PMT waveforms, enabling measurement of muon decay-in-orbit (DIO) decay times. The PBM, installed on the proton beamline, provides real-time proton beam monitoring. Additionally, a dedicated beam-masking system upstream of the transport solenoid entrance studies transport solenoid optics and beam dynamics.

**1. Experiment Setup** [Figure 4: see original paper] Monitor the timing structure of the muon beam in the phase-$\alpha$. Panel (a) shows the overview of the timing structure; Panel (b) is the zoom-in details and peak fittings in the short time window.

The detector was installed in the COMET Experimental Hall in mid-February 2023. A dedicated 8 GeV bunched proton beam from the J-PARC Main Ring (MR) strikes a graphite target to produce the secondary muon beam. This proton energy minimizes antiproton pollution while generating sufficient muons for physics requirements [26]. The beam spill cycle time is 9.2 s, with acceleration and flat-top times of approximately 0.6 s and 8.6 s, respectively. Beam power during Phase-$\alpha$ commissioning was 0.26 kW. While the original plan specified a 3 T magnetic field to guide the muon beam through the transport solenoid, the actual field used was only 1.5 T, resulting in wider muon beam extension. MBM was installed just after the transport solenoid exit, centered on the solenoid exit aperture. During installation, we introduced a 'local time' trigger signal from the Range Counter via an SMA interface to reset the MBM time to zero upon event triggering. Data were collected from March 3–5 and 9–15 with the secondary muon beam.

**2. Experiment Results** For Phase-$\alpha$ commissioning, MBM had two primary goals: characterizing the muon beam time structure and comparing it with the bunched proton time structure from J-PARC MR, and measuring the muon beam spatial profile to better understand beam production and transport.

Additionally, we assessed MBM' s long-term operational stability in the harsh environment.

The muon beam timing structure is a key concern. As noted, COMET requires a dedicated 8 GeV bunched proton beam to generate the secondary muon beam. In the COMET design, the J-PARC Main Ring synchrotron accelerates protons cycle-by-cycle, with each Main Ring cycle consisting of three bunches (type a) spaced by 1.17 µs and one bunch spaced by 1.76 µs (type b), which effectively reduces physical backgrounds from other beam particles. Due to low beam intensity in Phase-$\alpha$ commissioning, MBM recorded on average only 0.02 events per bunch, requiring superposition of many events to reveal a visible structure. However, timing resolution limitations from the Main Ring prevented precise bunch identification for triggered hits, so the time structure represents a superposition of four possibilities (aaab, aaba, abaa, baaa). We therefore expected a time structure with one large peak and six small peaks, with the large peak spaced 1.1 µs from small peaks and small peaks separated by 586 ns in the zoomed time window. By accumulating data from approximately 800 runs, we successfully plotted the muon beam timing structure shown in Fig. 4, which matches expectations well.

[Figure 5: see original paper] The 2D muon beam profile in COMET Phase-$\alpha$.

Another important measurement is the muon beam profile. We obtained the 2D profile shown in Fig. 5. During actual beam operation, the measured profile is not perfectly circular due to multiple interfering factors. One reason is the transport solenoid magnetic field of 1.5 T—half the design value for COMET Phase-I. Additionally, Phase-$\alpha$ detectors are installed at the solenoid exit without any magnetic field, plus scattering effects in air. Furthermore, the beam contains several charged particle types ($e^-$, $\mu^-$, $\pi^-$), each with different beam directions. These factors cause the beam to spread widely, resulting in different beam spots in the profile.

Phase-$\alpha$ commissioning ran from March 3rd to March 13th with a 1.5 T magnetic field. During this period, the muon beam operated stably, and we conducted detailed measurements of time and profile structures, reflected by the stable beam spot in Fig. 6. To comprehensively characterize beam profile features, we plotted the beam profile barycenter and detector counting rate, demonstrating long-term detector stability throughout Phase-$\alpha$ commissioning.

[Figure 6: see original paper] The long-term stability of the muon beam. Panel (a) shows the change of center location during the beam time; Panel (b) monitors the change of hit rates during the beam time.

After successful muon mode operation, we turned off the magnetic field for several hours, then inverted its direction to measure the anti-muon component in the "Mu+ Run,"studying beam composition and magnetic field effects. During the Mu+ Run, we also moved the beam masking system several times to validate beam optics and dynamics in the curved transport solenoid. Fig. 6 shows the beam center location and stable trigger rate throughout most of this period.

Notable beam jumps after Run 3257 were caused by magnetic field swaps and beam masking system movements.

[Figure 7: see original paper] The MBM-RC coincidence hit map and the movement of RC during the commissioning. Panel (a) shows that RC is located in the bottom right while Panel (b) displays that RC is moved to the top left.

To verify correct beam position identification, we performed coincidence measurements with the Range Counter by selecting first hits in each event, producing the hit maps shown in Fig. 7. Clear hot zones indicate the Range Counter position. By moving the Range Counter to different locations and recording relative positions, we validated MBM' s response to beam location. Fig. 7 shows beam spots at bottom right (Fig. 7(a)) and top left (Fig. 7(b)), corresponding to Range Counter movement from bottom right to top left, confirming MBM' s correct response to beam position.

## IV. Summary and Outlook

The first complete Muon Beam Monitor with 1 mm-wide scintillation fibers and X-Y SiPM readout has been designed and successfully used for COMET Phase-$\alpha$ commissioning. The detector achieves 1.6 ns time resolution and 1 mm spatial resolution with a 30 $\times$ 30 cm$^2$ beam window. We validated the monitor system with cosmic ray muons in the laboratory and verified MBM functionality through multiple beam tests, including measurements of muon and proton beam timing structures and profiles. MBM performance remains excellent.

Experience from COMET Phase-$\alpha$ commissioning is guiding further MBM upgrades for Phase-I operation. Compared to Phase-$\alpha$, Phase-I beam intensity will increase by approximately three orders of magnitude. We plan to upgrade the electronic readout to avoid pile-up events, including electronics capable of recording both charge and time information, and a more powerful DAQ system for much higher trigger rates. Additionally, since backend detectors must be installed inside the Detector Solenoid (DS) for Phase-I, which provides a 1 T high magnetic field environment [41], electronic components collecting SiPM signals must be placed outside the DS to avoid magnetic field damage. However, this location must also withstand strong neutron radiation effects in the harsh environment outside the solenoid. Strengthening electronics radiation hardness to avoid single-event upsets will be challenging. While much work remains to pin down exclusion limits or claim new physics discoveries, this effort drives cutting-edge technology through fundamental science and deserves continued pursuit.

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*Note: Figure translations are in progress. See original paper for figures.*