Commissioning of the Cylindrical Drift Chamber for the COMET experiment

Manabu Moritsu[*]

Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research
Organization (KEK), Tsukuba 305-0801, Japan
E-mail: moritsu@post.kek.jp

Yoshitaka Kuno, Yugo Matsuda, Yu Nakazawa, Saki Ohta, Hideyuki Sakamoto[†], Akira Sato, Ming Liang Wong[‡], TingSam Wong, Chen Wu, Hisataka Yoshida

Department of Physics, Osaka University, Toyonaka 560-0043, Japan

Xiaoshan Jiang, Hai-Bo Li, Yohei Nakatsugawa, Jie Zhang

Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, Beijing 100049, China

A cylindrical drift chamber (CDC) has been developed for the COMET Phase-I experiment. To search for the muon-to-electron conversion with a sensitivity of 3×10^{-15}, the CDC is required to have momentum resolution of 200 keV/c for 100-MeV/c electrons. In order to reduce the multiple scattering, we have selected a chamber gas mixture of 90% helium with 10% isobutane. Construction of the CDC was successfully conducted, and performance evaluation is being carried out. We have confirmed stable operation without a magnetic field thus far based on cosmic-ray tests. In this paper, the motivation, design, construction, and commissioning status of the CDC are presented.

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[*]Speaker.

[†]Present address: Center for Computational Science, RIKEN.

[‡]Present address: Université Clermont Auvergne.

1. Introduction

The COMET experiment aims to search for the neutrinoless coherent transition of a muon to an electron in the field of an aluminum nucleus, $\mu^- N \to e^- N$, which violates the lepton flavor conservation and has never been observed yet thus far [1, 2]. The process is extremely suppressed in the Standard Model even if the neutrino oscillation effect is taken into account. However, the conversion rate is predicted to be enhanced in most of well-motivated new physics models beyond the Standard Model. The goal of the COMET Phase-I is to explore the muon-to-electron conversion with a single event sensitivity of 3×10^{-15}, which is 100 times better than the current limit.

The experiment takes place at J-PARC with a high-quality pulsed beam and unprecedentedly powerful muon source. To search for the muon-to-electron conversion, negative muons are stopped in a target material and form a muonic atom with a nucleus. Within the Standard Model, fate of the muon is either muon decay in orbit (DIO) or nuclear muon capture with fractions of 39% and 61%, respectively for aluminum nucleus. Then, if the muon-to-electron conversion happens, we could observe an electron without neutrinos. Since the process is coherent, the emitted electron has a unique energy of 105 MeV for aluminum nuclei.

Whilst the signal of the muon-to-electron conversion is the mono-energetic 105 MeV electron, one of the significant backgrounds is a high-energy tail of the DIO electron distribution [3]. In order to distinguish the signal from the DIO background, good resolution of 200 keV/c is required in terms of the electron momentum measurement.

2. Cylindrical Drift Chamber

In the COMET Phase-I experiment, the converted electrons are detected with a cylindrical drift chamber (CDC) and trigger hodoscopes in a solenoidal magnetic field of 1 T. Figure 1 shows
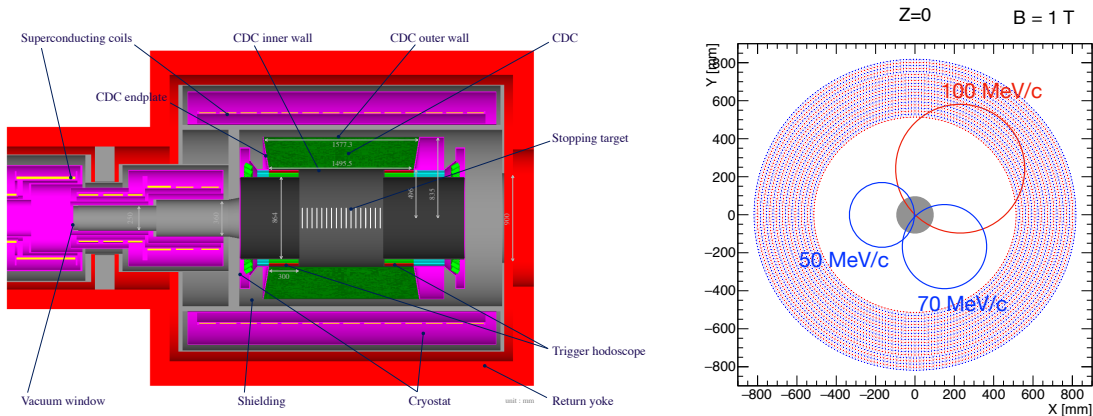
Figure 1: Schematic layout of the Cylindrical Detector System for the COMET Phase-I experiment. Muon beams come from the left side.

Figure 2: Cross-sectional view of the CDC at the center of longitudinal direction ($Z = 0$). Circles indicate trajectories of charged particles with corresponding momenta at a 1 T magnetic field.

a schematic layout of the Cylindrical Detector System. Muons, coming from the upstream, are stopped in aluminum target discs placed in the center of the detector solenoid, and transversely-emitted electrons are measured by the Cylindrical Detector System.

The CDC has a large inner diameter of approximately 1 m, because of the following two reasons. First, since the detector area is exposed to the beam flash at a prompt beam timing, the detectors have to avoid large-emittance beam stream. The second reason is to suppress the DIO-electron hits. The acceptance of the CDC is designed to open from around 70 MeV/c as illustrated in Fig. 2. Most of the DIO-electrons have less than 50 MeV/c momenta, and therefore do not reach the CDC, which is quite helpful to mitigate the CDC hit occupancy.

Specifications of the CDC is listed in Table 1. The inner and outer cylinders are made of carbon-fiber-reinforced plastic (CFRP) with thicknesses of 0.5 and 5.0 mm, respectively. The end-plates are made of 10-mm aluminum with slightly tapered shape to sustain a wire tension load. The number of layers are 18 with 2 guard layers as the innermost and outermost layers. An alternated all stereo layer configuration with ±(64–75)-mrad tilt angles is designed to achieve good spatial resolution for the longitudinal direction. A partial cross section of the CDC cell structure is shown in Fig. 3. Although the cell shapes are slightly distorted according to their positions, the typical single cell geometry is almost square with 16.0-mm height and 16.8-mm width as shown in Fig. 4.

In order to accomplish the required momentum resolution of 200 keV/c for the 105-MeV/c electrons, the CDC is designed to reduce material thickness to suppress the multiple scattering

Table 1: Specifications of the CDC [2].

Inner wall (CFRP)	Length	1495.5 mm
	Radius	496.0–496.5 mm
	Thickness	0.5 mm
Outer wall (CFRP)	Length	1577.3 mm
	Radius	835.0–840.0 mm
	Thickness	5.0 mm
Number of layers	Sense layer	18
	Guard layer	2
Stereo angle		±(64–75) mrad
Cell size	Height	16.0 mm
	Width	16.8 mm
Sense wire	Material	(Au-plated) W
	Diameter	25 μm
	Number of wires	4,986
Field wire	Material	(unplated) Al
	Diameter	126 μm
	Number of wires	14,562
Gas	Mixture	He:iC$_4$H$_{10}$ (90:10)
	Volume	2,084 ℓ
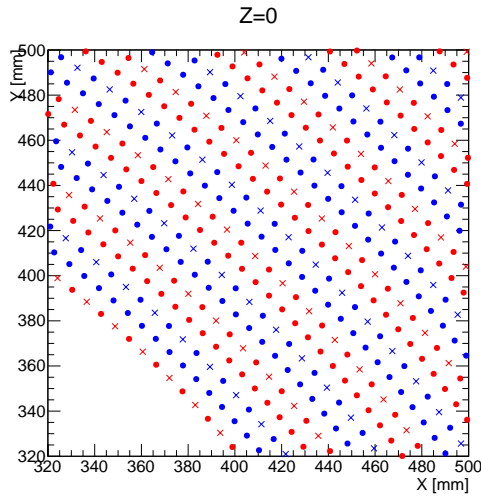
Figure 3: A partial cross section of the CDC cell structure. The crosses and circles indicate sense and field wires. The red and blue colors represent positive and negative stereo angles.
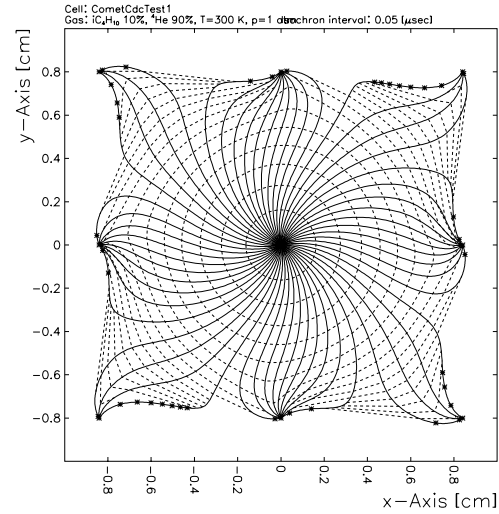
Figure 4: Typical single cell layout with drift lines and isochrones of 50-ns intervals at 1-T magnetic field with a sense wire voltage of 1800 V.

Table 2: Properties of the He:iC$_4$H$_{10}$(90:10) gas mixture at 20°C and 1 atm. Values of energy loss, primary ions, and total ions are for minimum ionizing particles, computed from [4]. Values of drift velocity and longitudinal diffusion are at 1000-V/cm electric field, obtained from [5, 6].

Parameter	Value
Mixture He : iC$_4$H$_{10}$	90:10
Radiation length	1400 m
Energy loss	0.88 keV/cm
Primary ions	13.5 /cm
Total ions	29.5 /cm
Drift velocity	∼2.2 cm/μs
Longitudinal diffusion	∼160 μm for 1-cm drift

which dominates momentum resolution in this low energy region. Hence, 90% helium with a quencher of 10% isobutane is selected as the chamber gas mixture. Properties of the He:iC$_4$H$_{10}$ (90:10) gas mixture is summarized in Table 2. Since low-Z materials have a small photoelectric cross section, they have an additional advantage to reduce background hits caused by low-energy photons from the muon stopping target.

3. Construction of the CDC

The aluminum endplates and the CFRP outer cylinder were fabricated before wire stringing. Wire feedthrough holes were precisely drilled on the endplates with tolerances of 0.05 mm for the position and 0.01 mm for the diameter. Wire stringing for the 19,548 total wires was per-
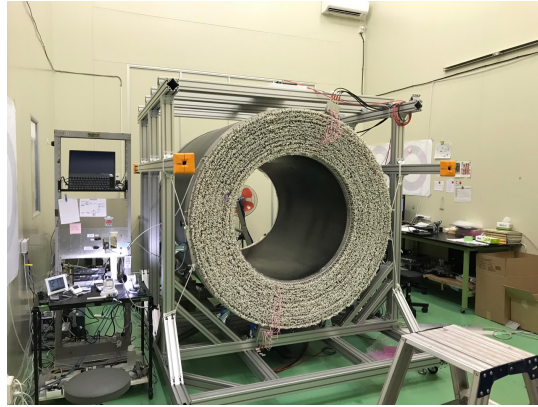
Figure 5: Photograph of the CDC taken from the upstream side.

formed after attaching the endplates with the outer cylinder. We use gold-plated tungsten wires with 25-μm diameter for the sense wires, and unplated aluminum wires with 126-μm diameter for the field wires. During the whole period of stringing, the room conditions were kept within 19.5–23.5°C temperature and 30–55% relative humidity. To compensate an estimated total wire tension of 1.4 ton, a pre-stress were applied between the endplates in advance and released appropriately as the wires were strung from outside to inside. The wires are fixed at feedthrough pipes with climping. The nominal tension weights for the sense and field wires were set to be 50 and 80 g, which correspond to the gravitational sags of 50 and 120 μm at the center, respectively. We confirmed that the sag for the sense wires was controlled between 48 and 61 μm, and the sag differences between the sense and surrounding field wires are kept within less than 100 μm [7].

The 0.5-mm thick CFRP inner cylinder was installed after the wire stringing to close the gas volume of 2,084 litters. The gas tightness was checked with a helium gas, and leak points were sealed with silicone gum. Figure 5 shows a photograph of the CDC after completion.

4. Readout Electronics

We use readout frontend electronics boards developed for the Belle-II CDC [8] with appropriate modifications. Each board has 48 input channels, 6 amplifier-shaper-discriminator chips, 6 ADCs and an FPGA. The ADC provides 10-bit pulse-height information with a 30-MHz sampling. The TDC function is implemented in the FPGA with a 960-MHz digitization. In order to withstand a severe radiation environment in the COMET Phase-I experiment, the FPGA firmware is developed with an auto-recovery scheme tolerable against 10^{12} cm^{-2} for 1-MeV equivalent neutron fluence [9].

5. Performance Test

CDC performance tests using cosmic rays are being carried out. Stable operation of the CDC was established with the He:iC$_4$H$_{10}$ (90:10) gas mixture and with an applied high voltage up to 1850 V. Figure 6(a) shows a residual distribution obtained from the deviation of drift distance from

(a) Residual distribution

(b) Spatial resolution vs DCA
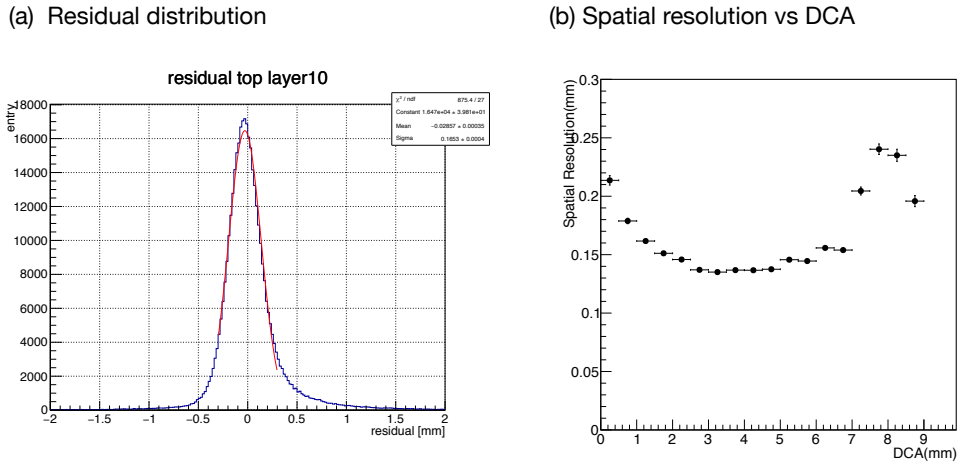
Figure 6: (a) Residual distribution for a central layer at 1825 V. The red line denotes a Gaussian fitting result of the core part. (b) Spatial resolution versus distance of closest approach (DCA) between a hit wire and a reconstructed track. The spacial resolution here includes a tracking uncertainty.

the distance of closest approach (DCA) between a hit wire and a reconstructed track. The spatial resolution was extracted from the residual distribution by fitting tracks excluding one layer, and estimated to be less than 170 μm at central layers. Note that the resolution here includes a tracking uncertainty. Figure 6(b) shows a spatial resolution versus DCA. While the resolution is smaller than 140 μm around a middle range of the DCA, it tends to be larger near the sense wire and field wires. A relatively small number of primary ions (see Table 2) deteriorates a spatial resolution in the small DCA region, and a distortion of the electric field near the field wires affects the resolution in the cell edge region. Hit efficiency is estimated to be higher than 98%.

We have demonstrated that the CDC shows a decent performance as expected, and will proceed to detailed evaluation in a magnetic field after construction of the detector solenoid magnet.

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