Commissioning of the Cylindrical Drift Chamber for the COMET experiment

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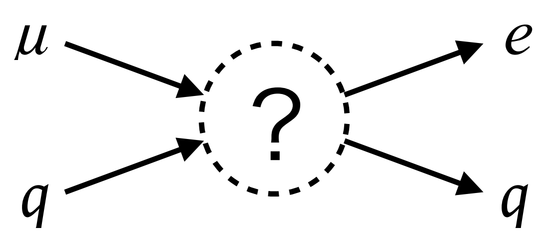
on behalf of the COMET Collaboration

European Physical Society Conference on High Energy Physics (EPS-HEP2019)
11th July 2019, Ghent, Belgium

μ-e conversion & COMET

- **Muon-to-electron conversion:**
  - Neutrinoless coherent transition in nuclear field
  - Violates the Lepton Flavor conservation
  - Search for NEW physics beyond the Standard Model

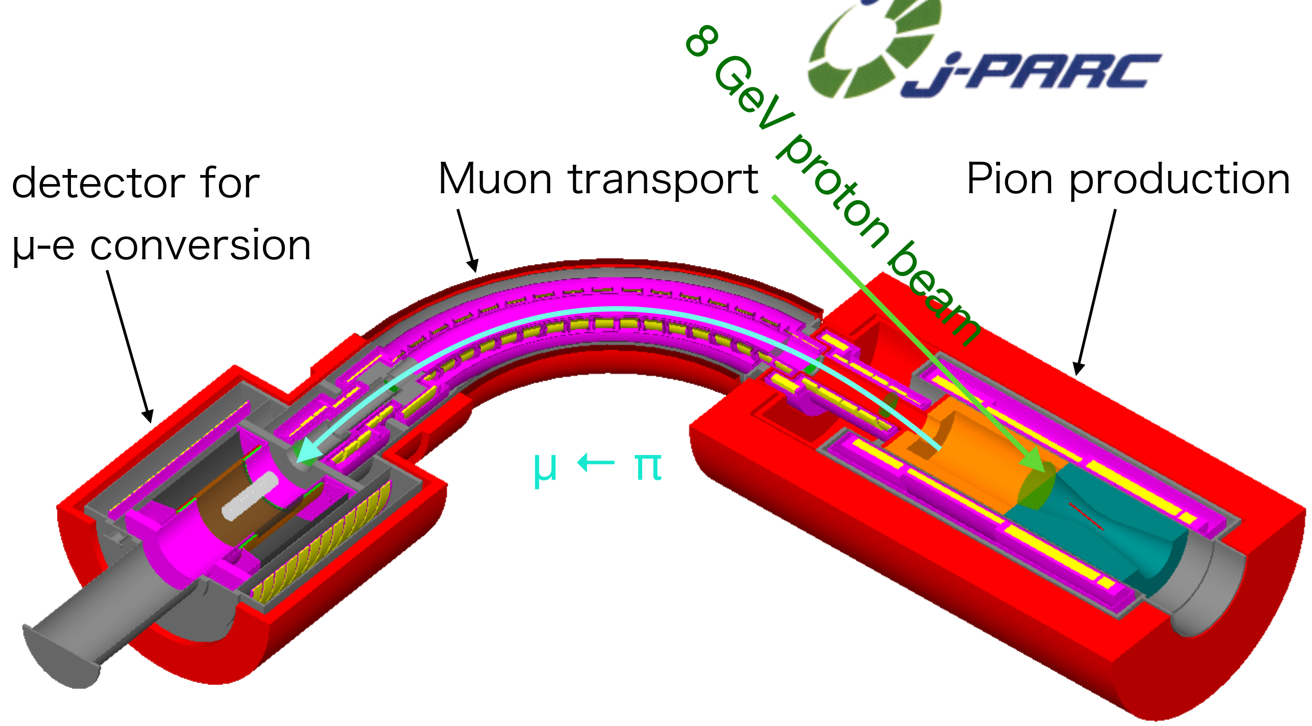
$$\mu^- + N \rightarrow e^- + N$$



- **The COMET experiment:**
  - Explores the μ-e conversion at **J-PARC** with single event sensitivity of
    - Phase-I: **3×10^{-15}** (×100 improvement)
    - Phase-II: **3×10^{-17}** (×10,000 improvement)

COMET talk by Y.Fujii
17:30, 12/July, room-D

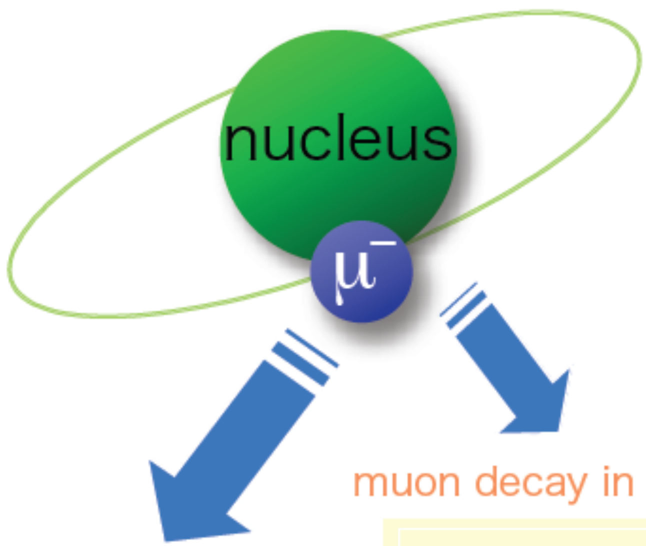
COMET Phase-I



Signal & background

Fate of muonic atom

1s state in a muonic atom



muon decay in orbit (39% in Al)

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture (61% in Al)

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

If μ-e conversion happens,

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

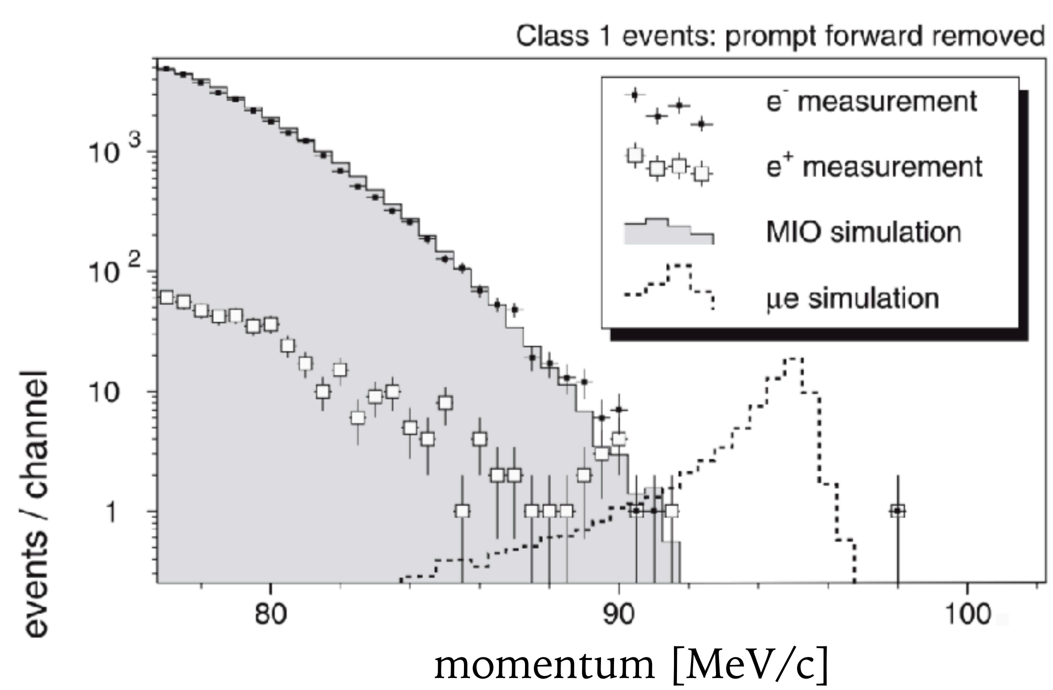
single mono-energetic electron

$$E_{\mu e} = m_\mu - B_\mu - E_{\mathrm{rec}} = 105\ \mathrm{MeV\ for\ Al}$$

Current upper limit

SINDRUM-II, EPJ C47, 337 (2006)

Br(μ^- Au $\rightarrow$ e^- Au) < **7×10^{-13}**



Signal & background

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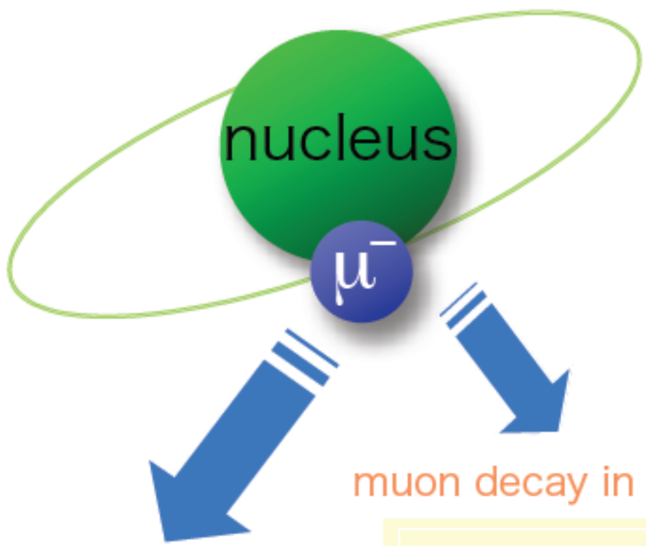

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DIO

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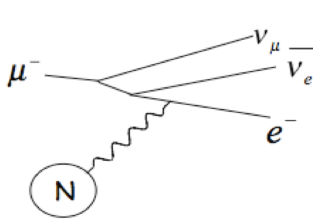
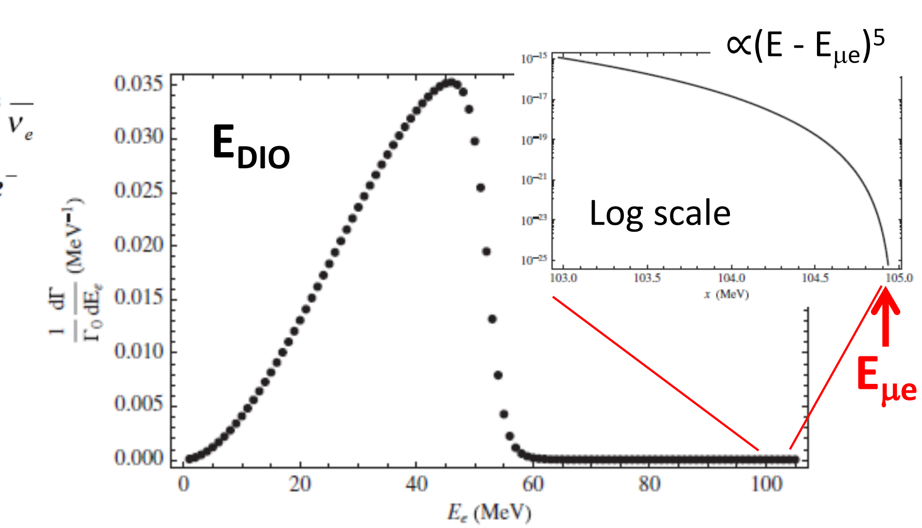
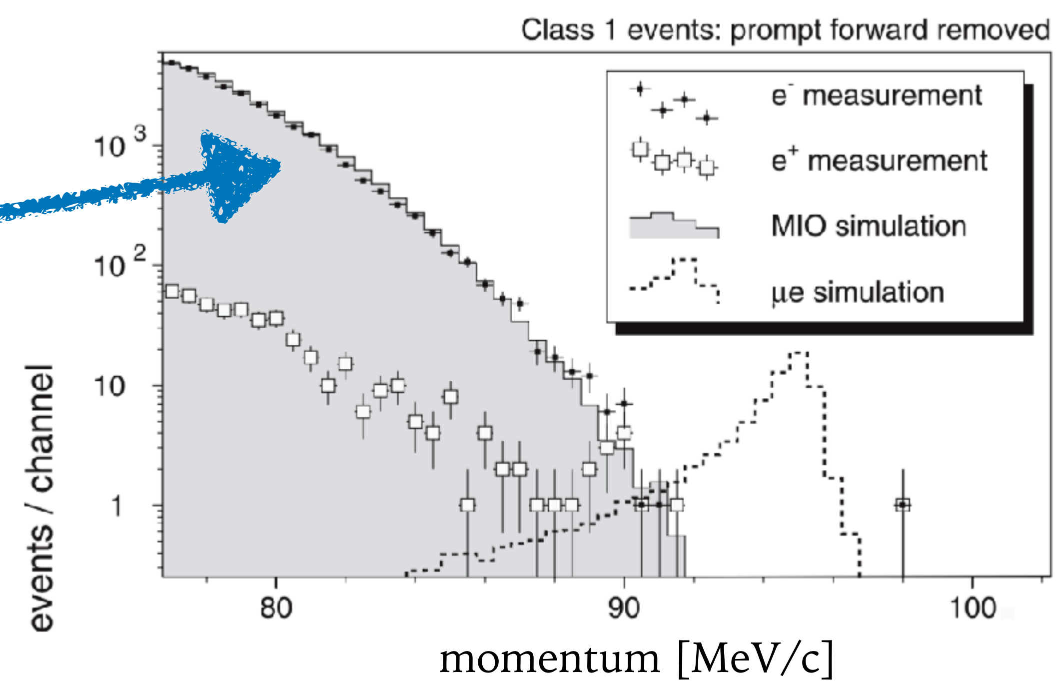
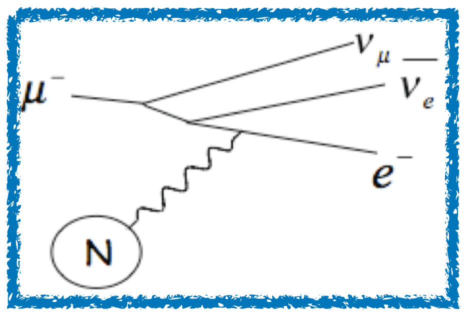




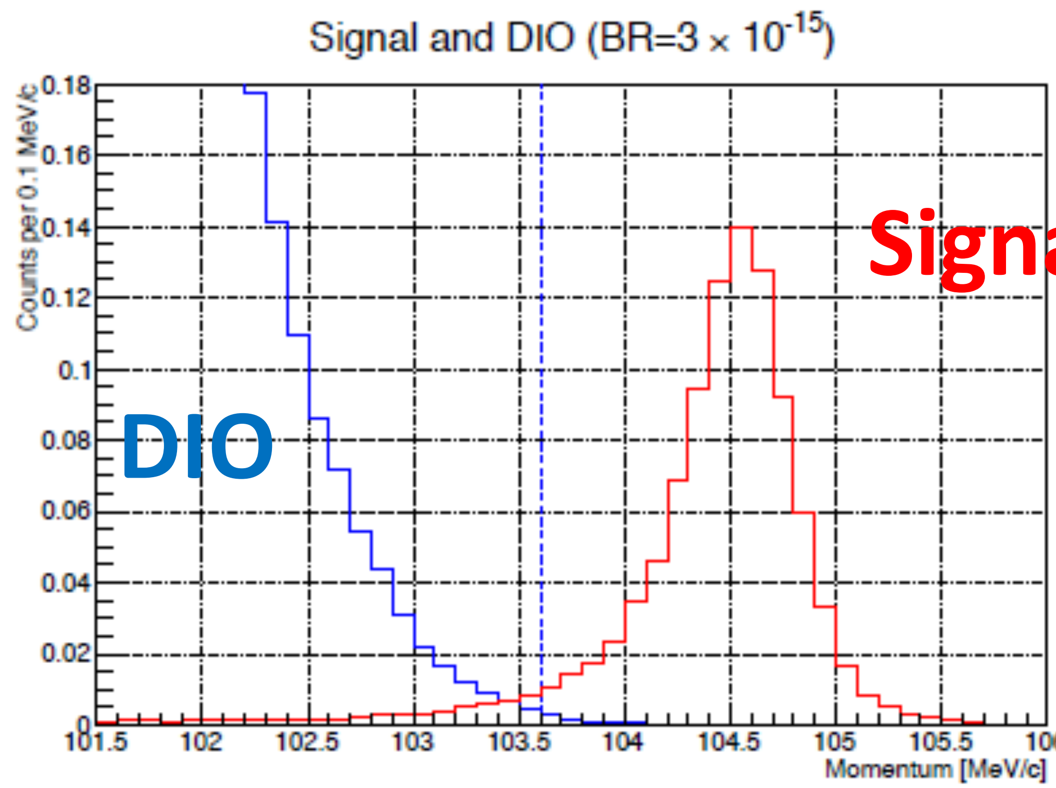


Requirement

DIO Background



COMET Phase-I Simulation



Electron momentum [MeV/c]

Signal

μ-e conversion

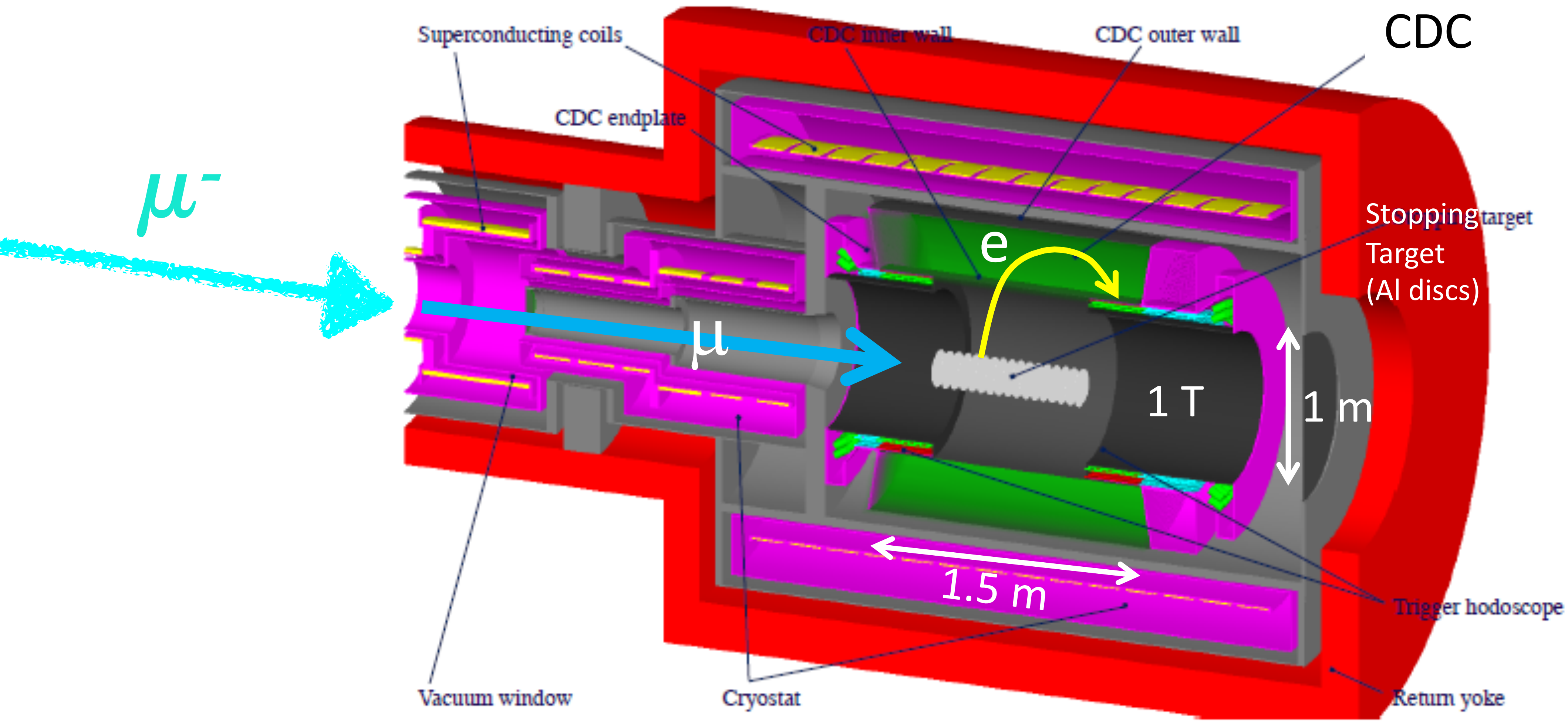
$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

To distinguish the signal from the background,

- Required momentum resolution is **200 keV/c (0.2%)** for 105 MeV/c.

COMET CDC

COMET Phase-I Detector System



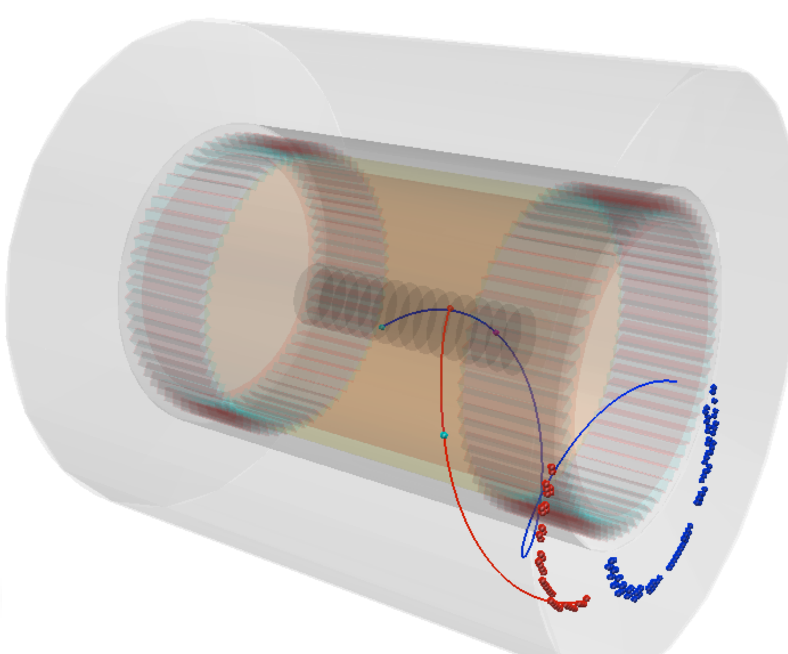
17 discs
50-mm spacing
100-mm radius
0.2-mm thickness

Dedicated system to μ-e conversion search

- **Cylindrical Drift Chamber (CDC)**
  - Curled-trajectory tracking in 1 T

\+

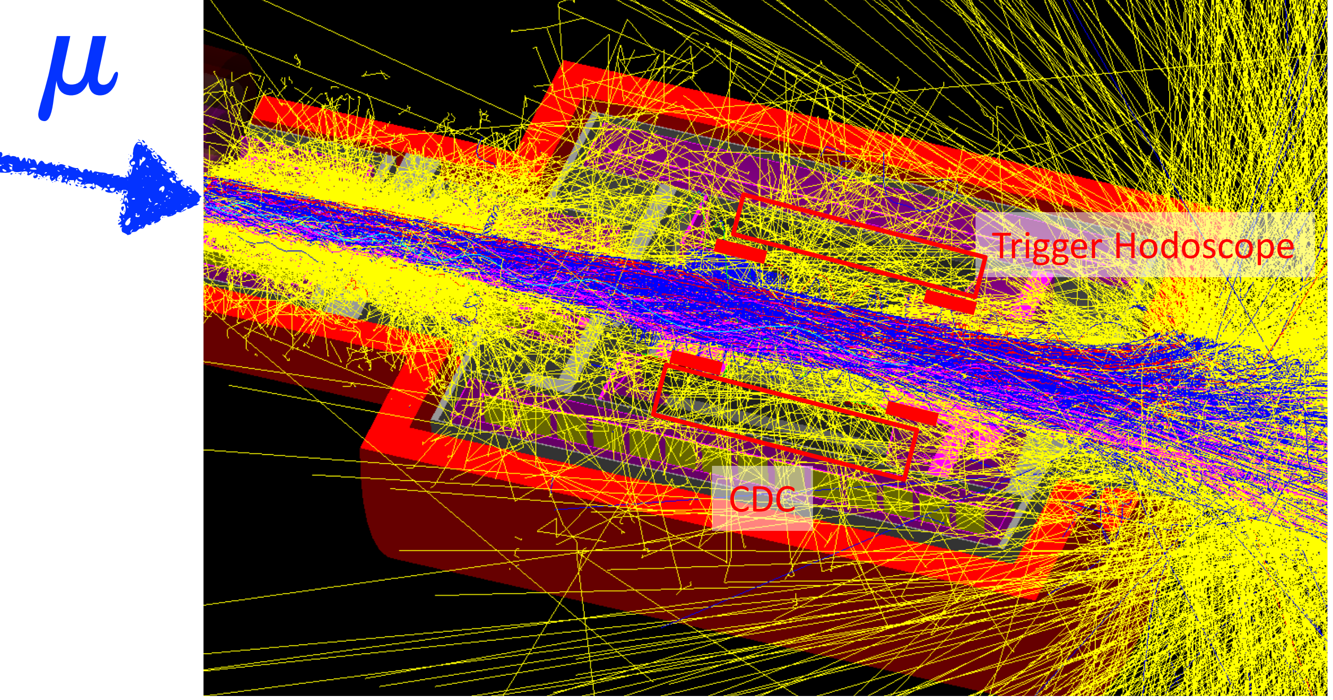
- **Trigger Hodoscopes**
  - Scintillator + Acrylic Cherenkov at inner side



Design of CDC

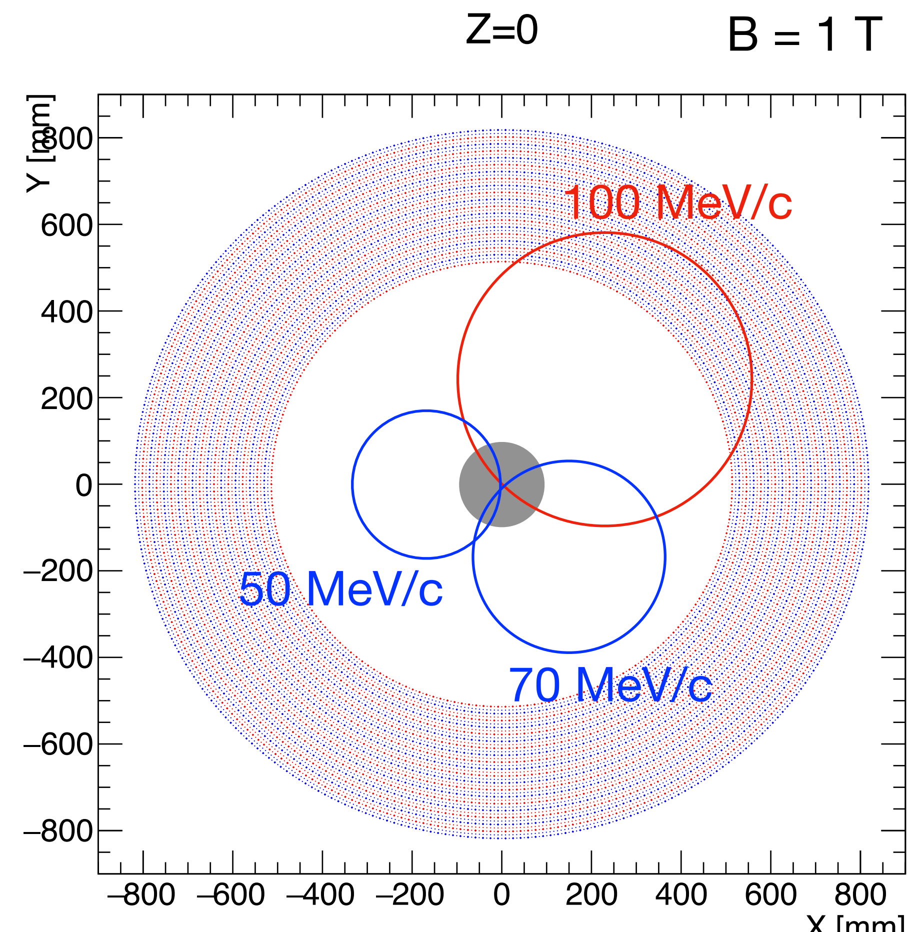
① Large inner diameter of ~1 m

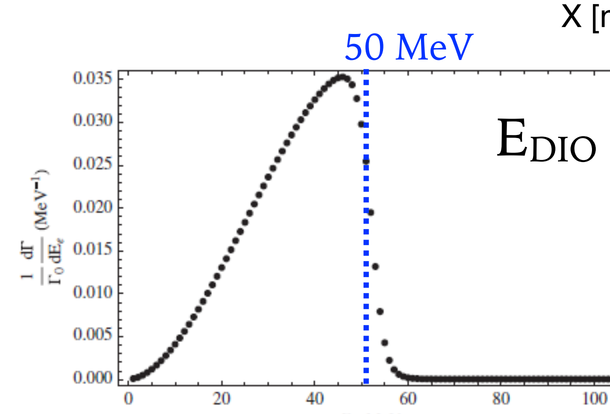
to avoid beam flash



yellow: phonons

to suppress DIO-electron hits





CDC acceptance > 70 MeV/c
Most of DIO < 50 MeV/c

Design of CDC

② Low-mass chamber

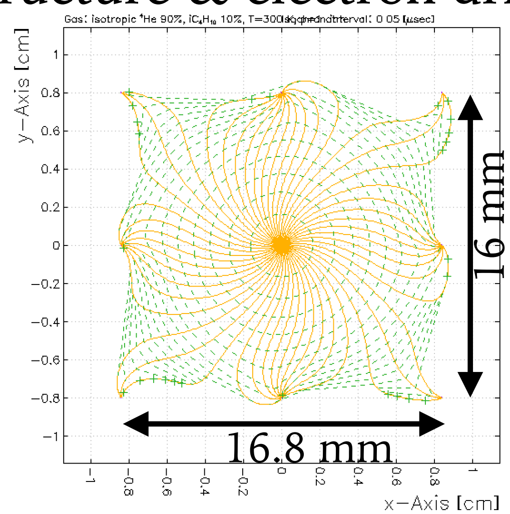
to suppress multiple scattering for good momentum resolution

- **He : iC_4H_{10} (90:10)** gas mixture X_0 = 1310 m
- **Aluminum field wires** with 126-μm diameter (unplated)
- Thin CFRP inner wall with **0.5 mm**

③ Alternating all stereo layer: 64—75 mrad

for good resolution in longitudinal direction

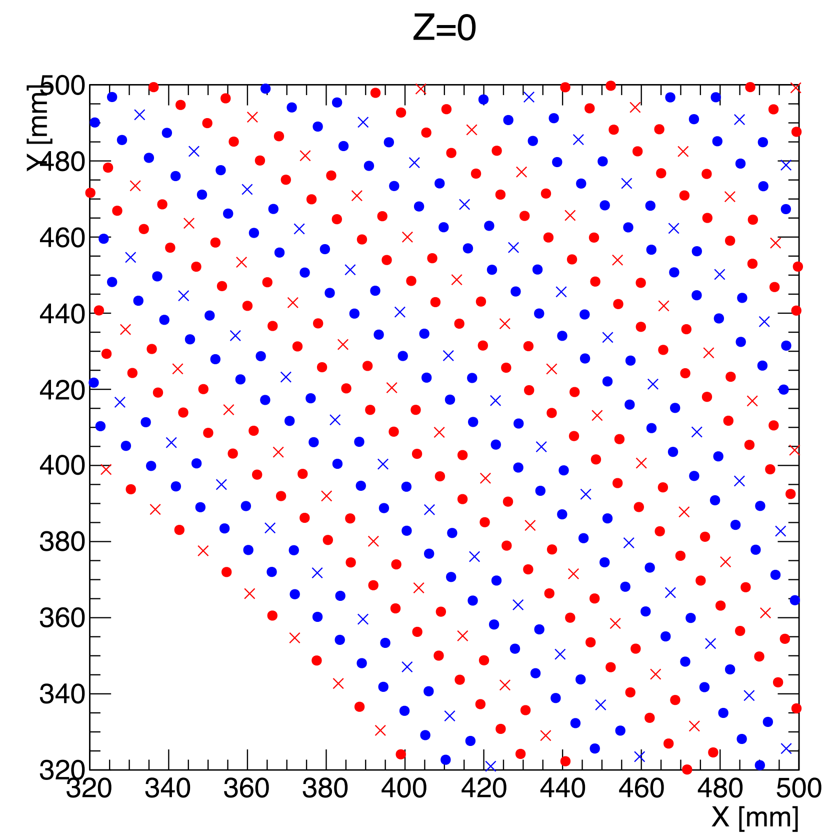
Cell structure & electron drift lines



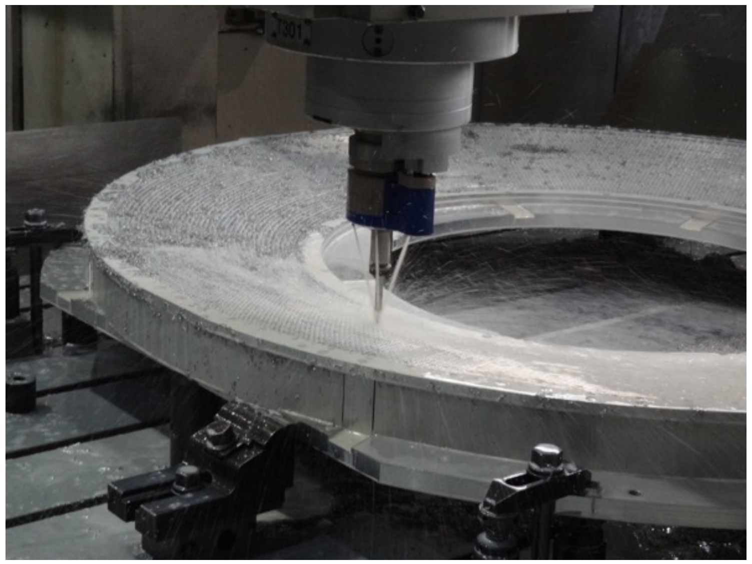
× sense wire
• field wire

Stereo angle:
\+ -

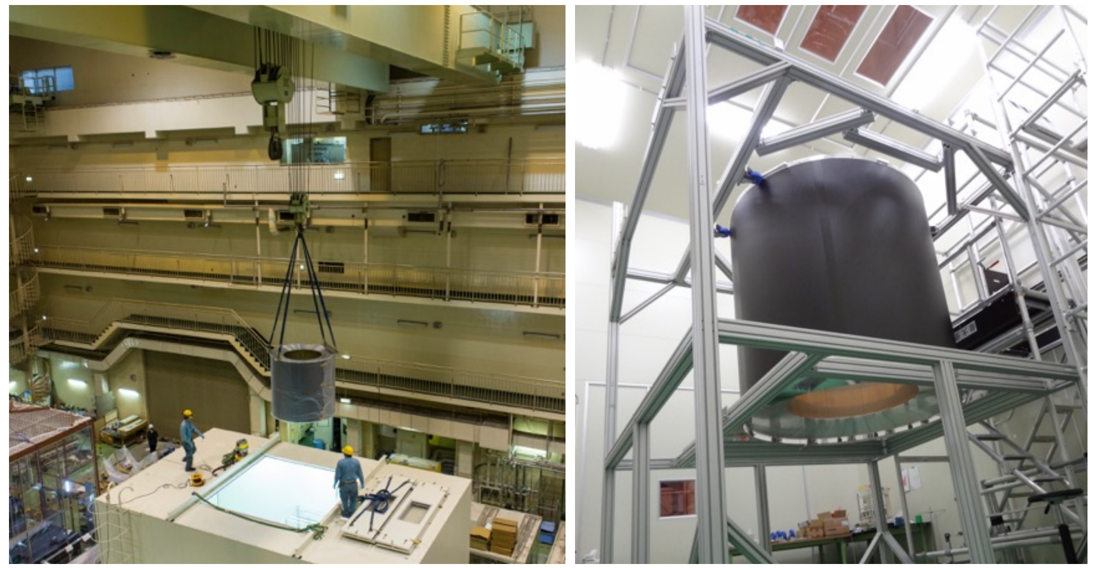
20 layers in total



Construction of CDC

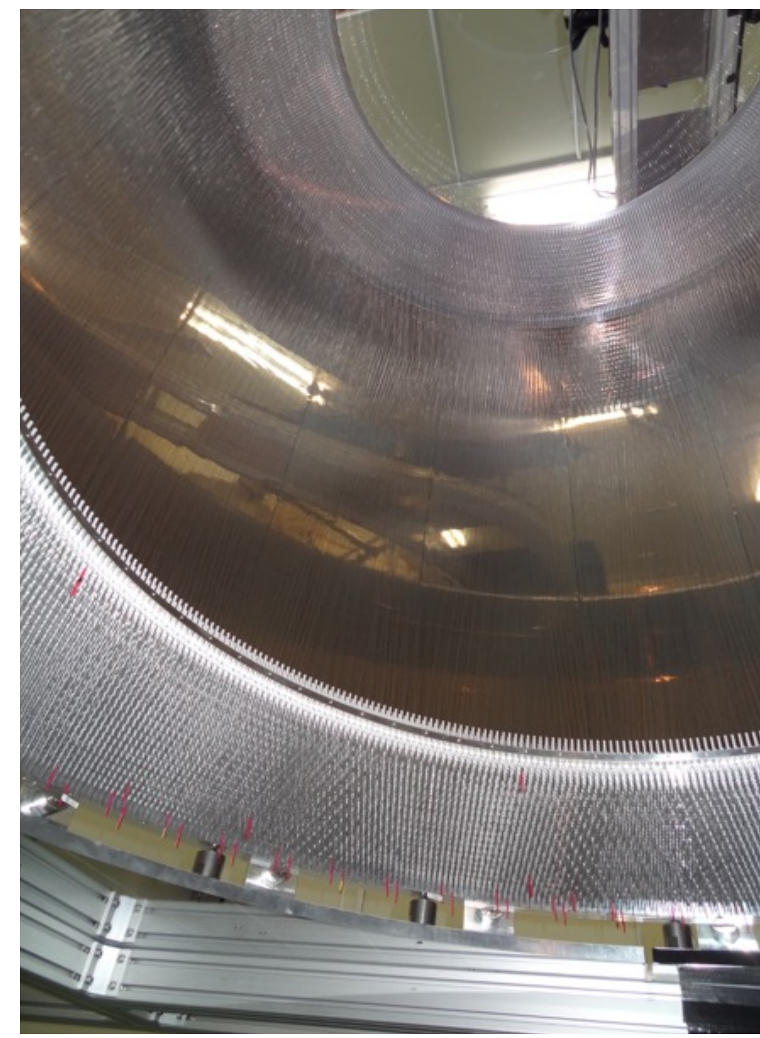


Drilling holes on endplates
with precision of 50 μm



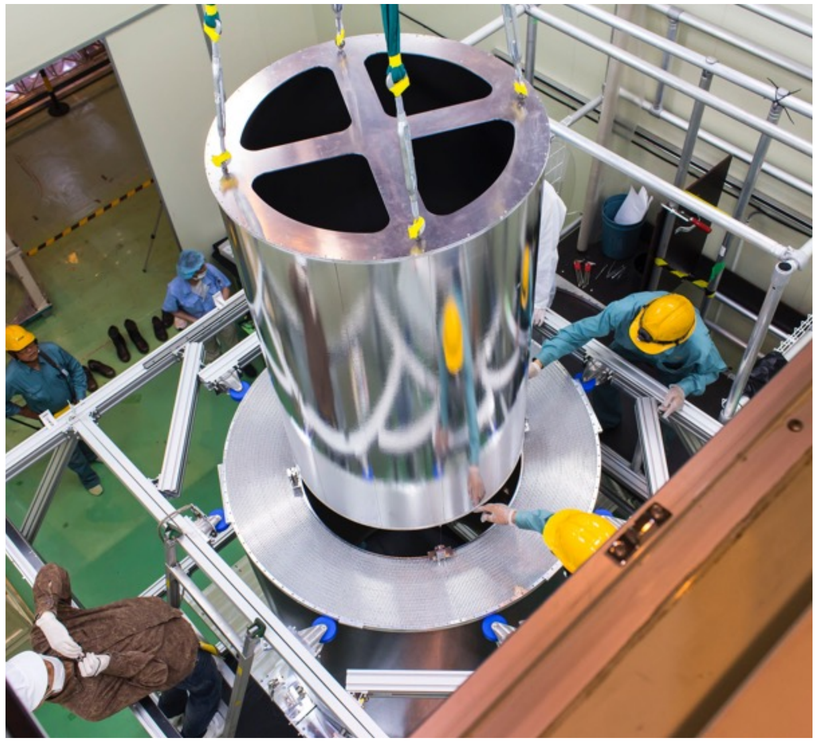
Outer structure was transported to a KEK
assembly hall, and set on a wire stringing cradle.

Wire stringing and tension measurement
for 19,548 wires were carried out in a half year.

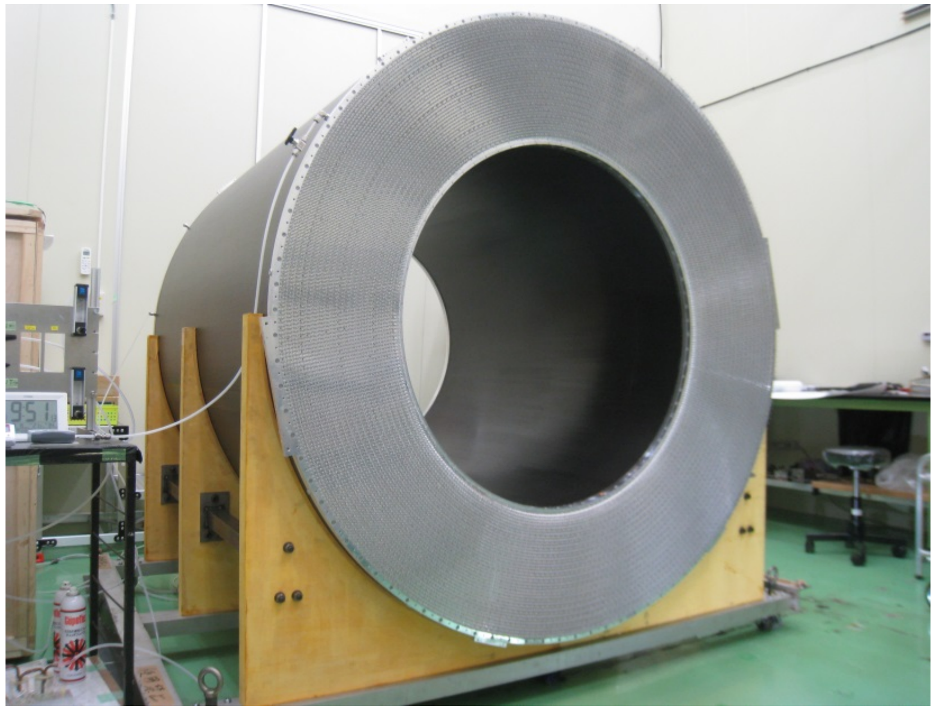


View from the down side after completion
(all the wires have stereo angles)

Construction of CDC

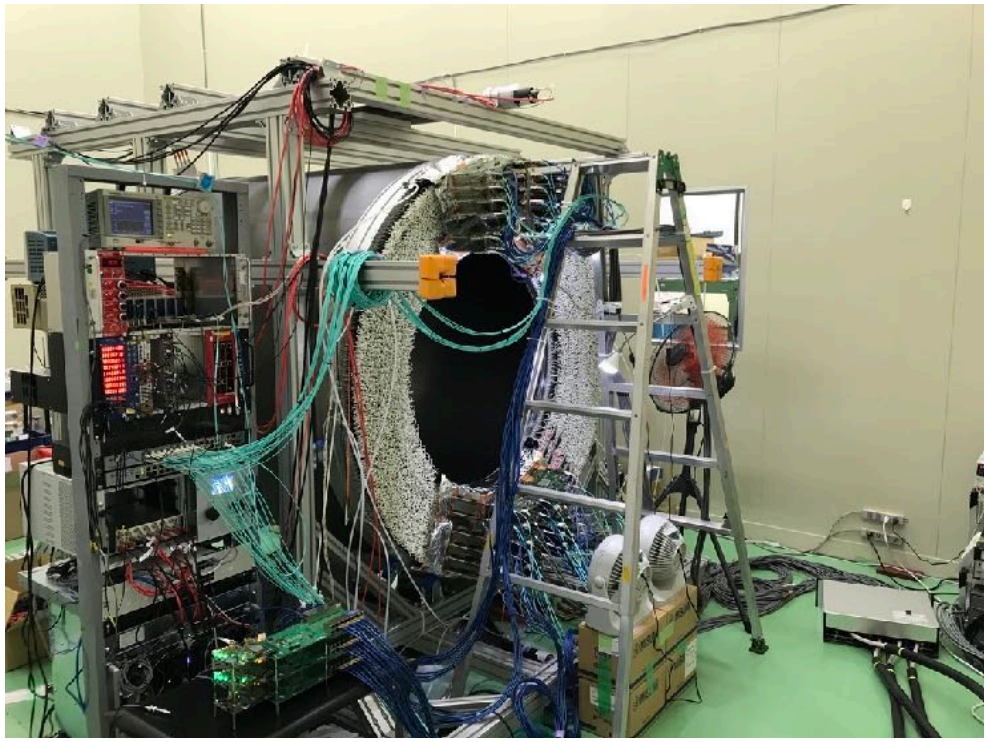


Installation of inner wall
made of 0.5-mm thick CFRP



Completion of whole structure

Cabling from feedthroughs to HV, RO & GND



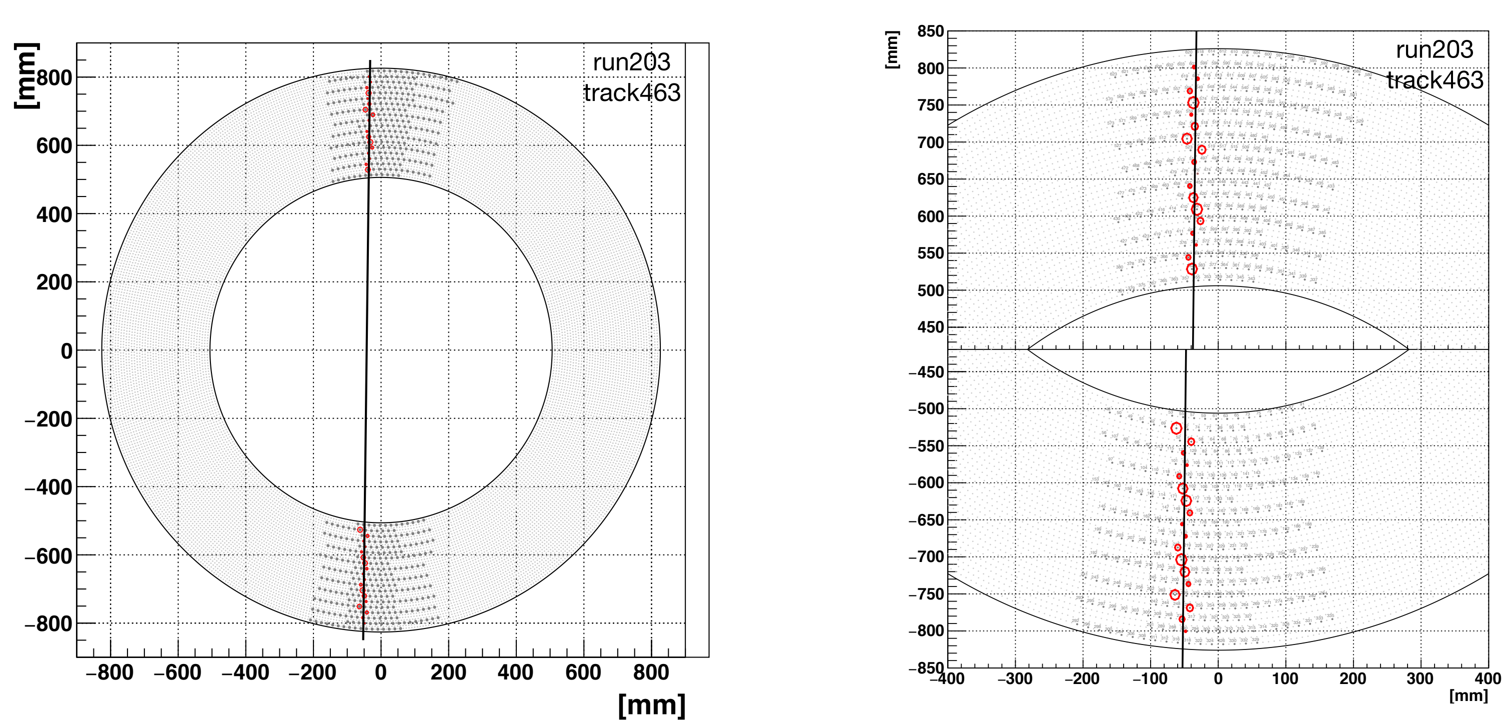
Cosmic-ray test started !!

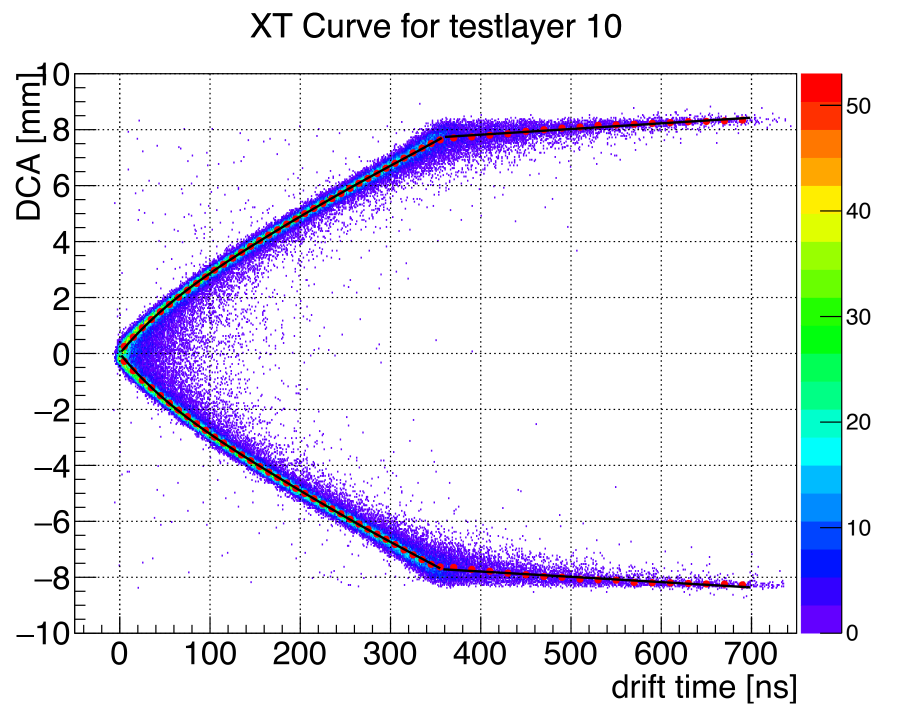
Performance tests

- CDC performance tests using cosmic rays are being carried out.
- We have obtained spacial resolution of ~165 μm & efficiency of ~98% so far.
- The performance tests will be continued in this year to precisely investigate whole region of the CDC.

(a) Event Display

(b) Zoom view





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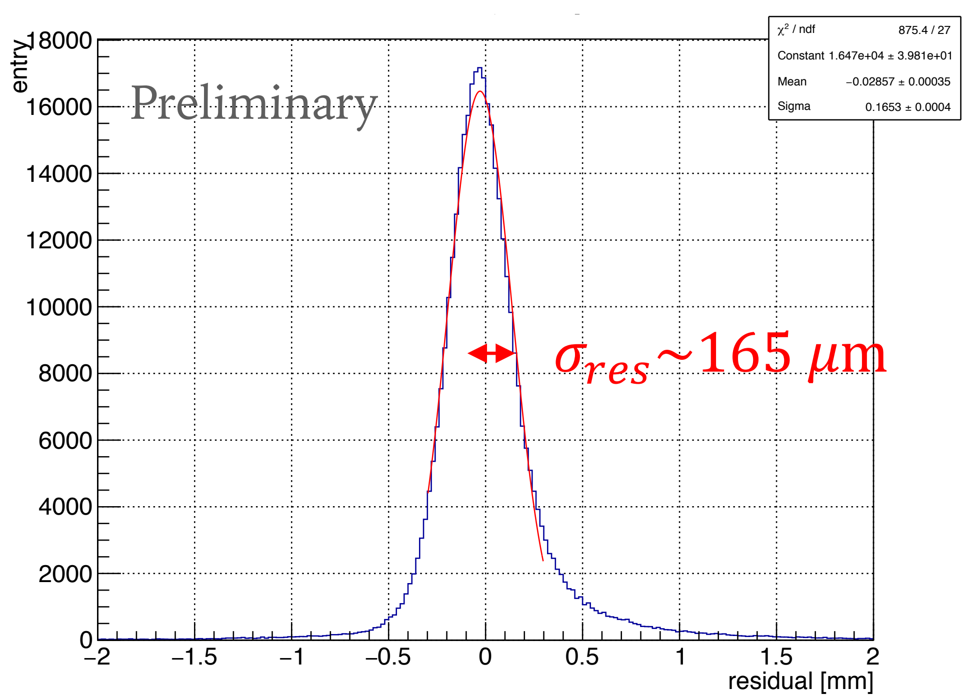
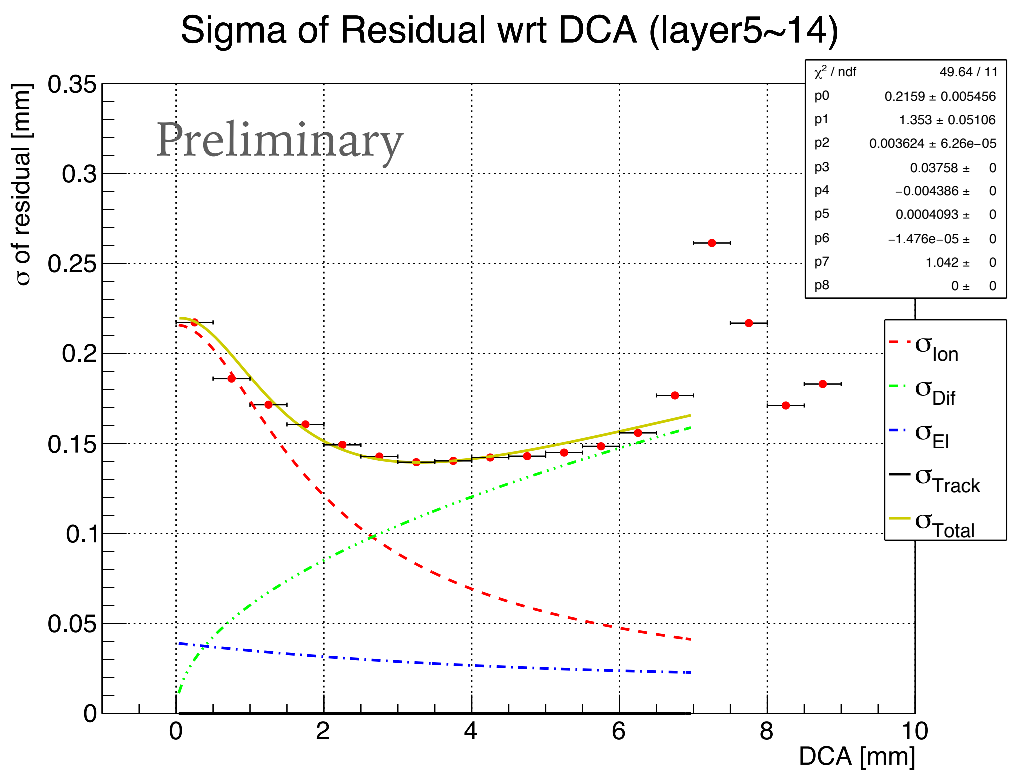


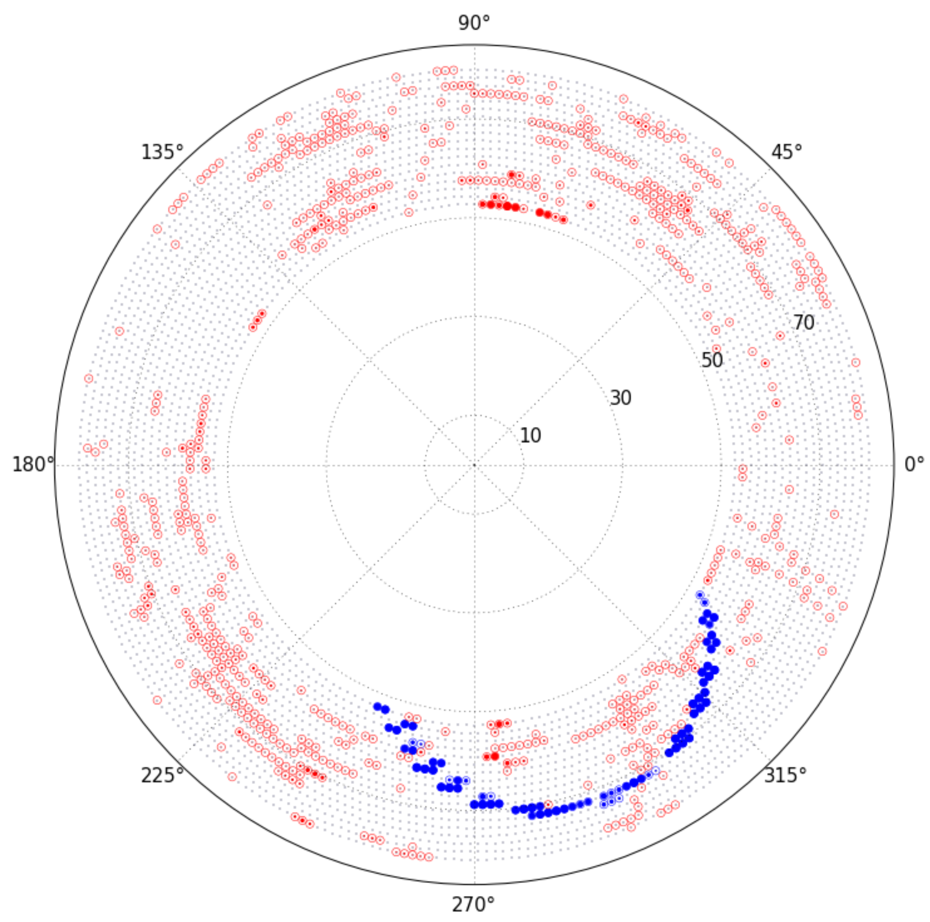


CDC high-level trigger

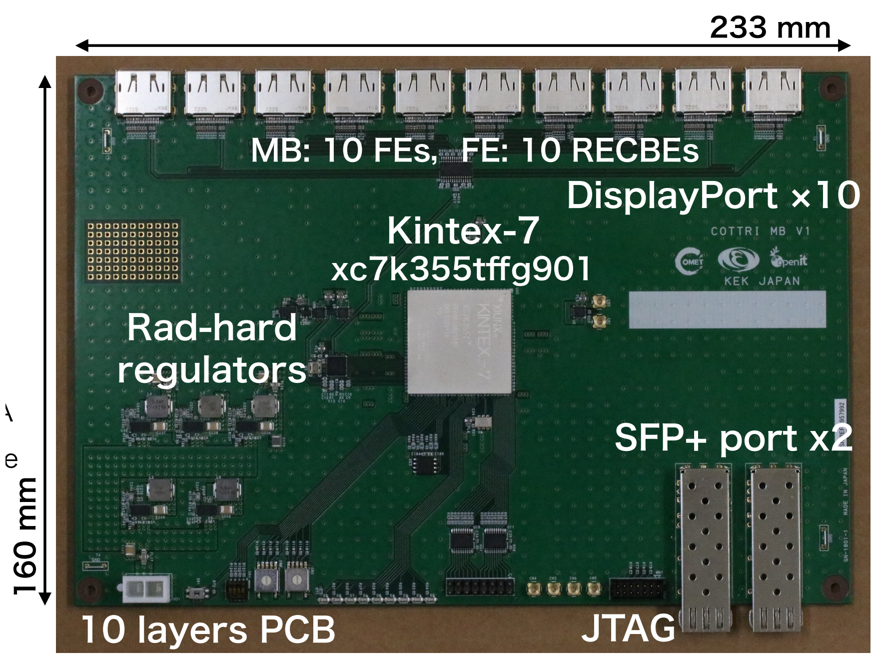
Fast Online Trigger using FPGA-based Event Classification

- 1st Level trigger rate from Trigger Hodoscopes **~27 kHz**
- Have to reduce in 2nd level trigger using CDC hit information
- **FPGA-based event classification** works
  - **BG rejection: 93% —> 2nd LV trig ~1.9 kHz**
  - Signal retention: 99%

Talk by Y.Nakazawa
11:45, 12/July, room-B



COTTRI (COmeT TRIgger) board



Prospects

- After cosmic-ray test, CDC will be transported from KEK to J-PARC (80-km movement).
- Soon after the Detector Solenoid magnet becomes ready, we will start **CDC full commissioning with magnetic field.**

Outer & inner cylinder of Detector Solenoid was completed.

Summary

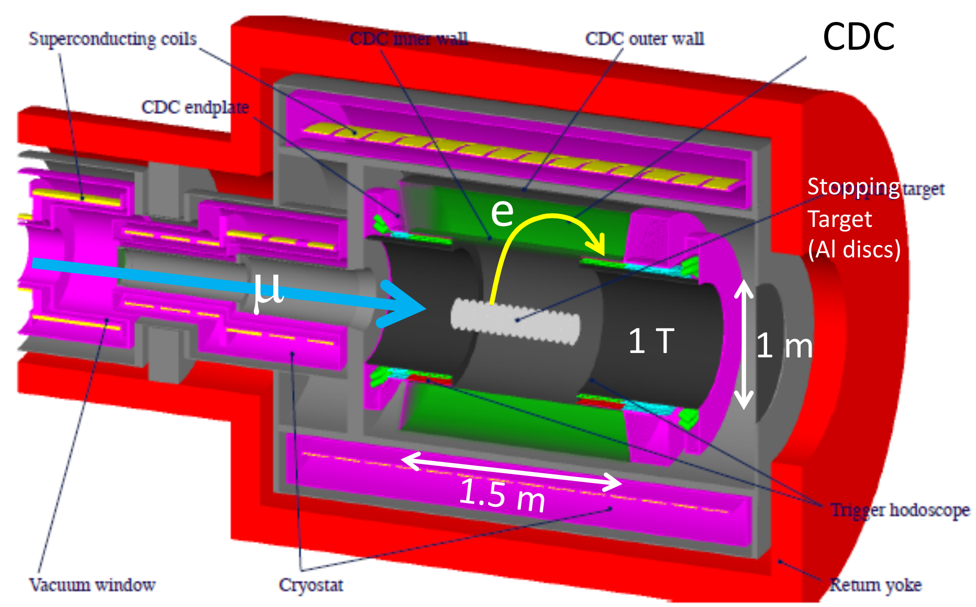
- The COMET experiment aims to search for the μ-e conversion. Preparation for the COMET Phase-I is intensively in progress.
- Cylindrical detector system is used for the Phase-I physics measurement.
- **COMET CDC** is designed to achieve 200-keV/c (0.2%) momentum resolution for 105-MeV/c signal electrons.
- Construction of CDC was successfully completed.
- Performance tests are ongoing and decent resolution & efficiency are obtained so far.
- After the detector solenoid becomes ready, we will start CDC full commissioning with magnetic field.

Backup

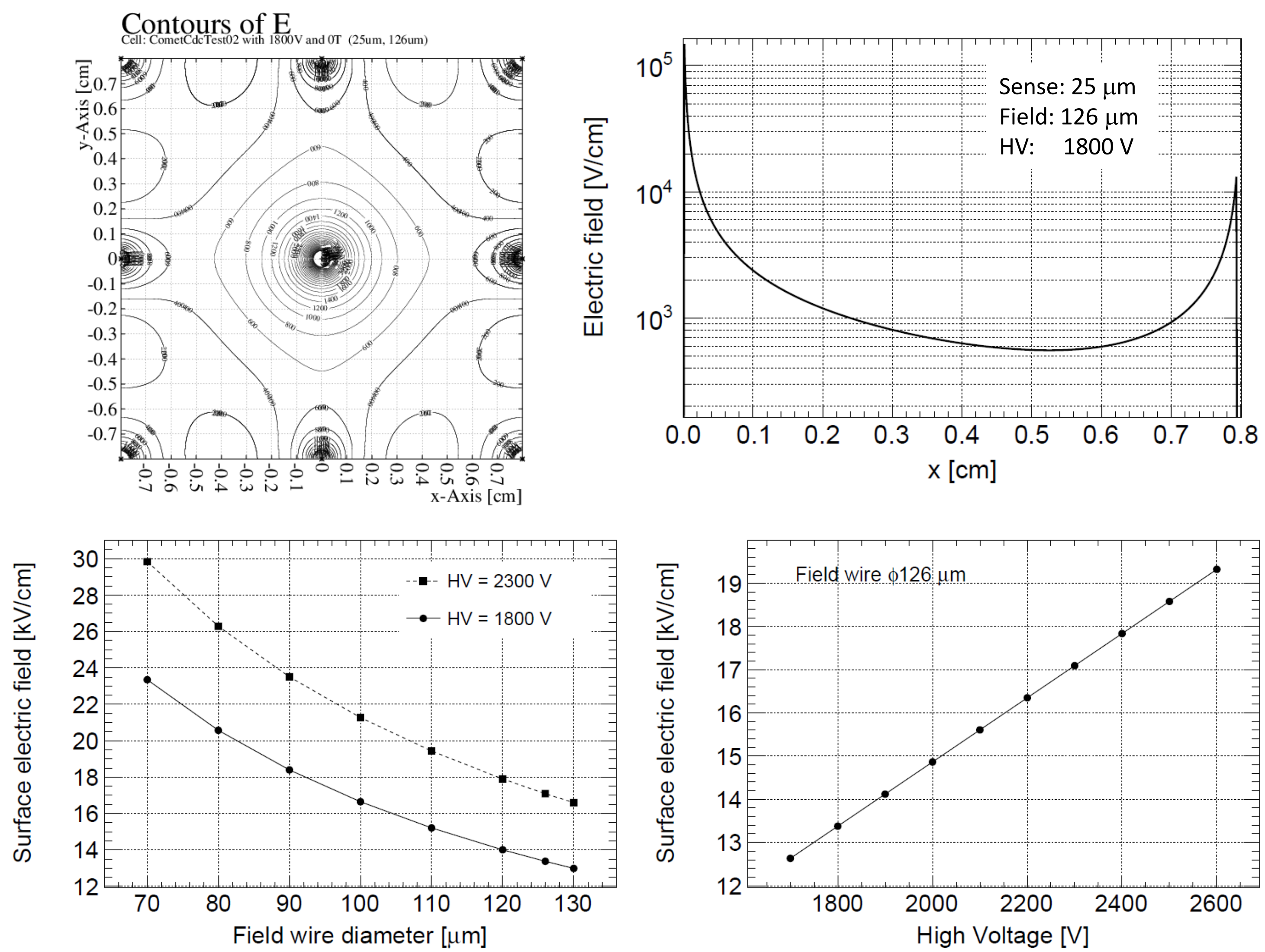
CDC specifications

Table 7.1: Main parameters of the CDC.

Inner wall	Length	1495.5 mm
	Radius	496.0∼496.5 mm
	Thickness	0.5 mm
Outer wall	Length	1577.3 mm
	Radius	835.0∼840.0 mm
	Thickness	5.0 mm
Number of sense layers		20 (including 2 guard layers)
Sense wire	Material	Au plated W
	Diameter	25 μm
	Number of wires	4986
	Tension	50 g
Field wire	Material	Al
	Diameter	126 μm
	Number of wires	14562
	Tension	80 g
Gas	Mixture	He:i-C_4H_{10} (90:10)
	Volume	2084 L



Electric field, drift velocity, etc



Gas	X_0 (m)	W (eV)	$\frac{dE}{dx}^{MIP}$ (keV/cm)	n_T^{MIP} (cm^{-1})	n_p^{MIP} (cm^{-1})
He:i-C_4H_{10} (85:15)	954	38	1.14	40	18
He:i-C_4H_{10} (90:10)	1310	39	0.88	29	14
He:i-C_4H_{10} (95:5)	2102	40	0.61	19	9
He:C_2H_6 (50:50)	630	32	1.63	60	27
He:CH_4 (80:20)	2166	39	1.47	17	11
He:CH_4 (90:10)	3073	40	0.47	13	8

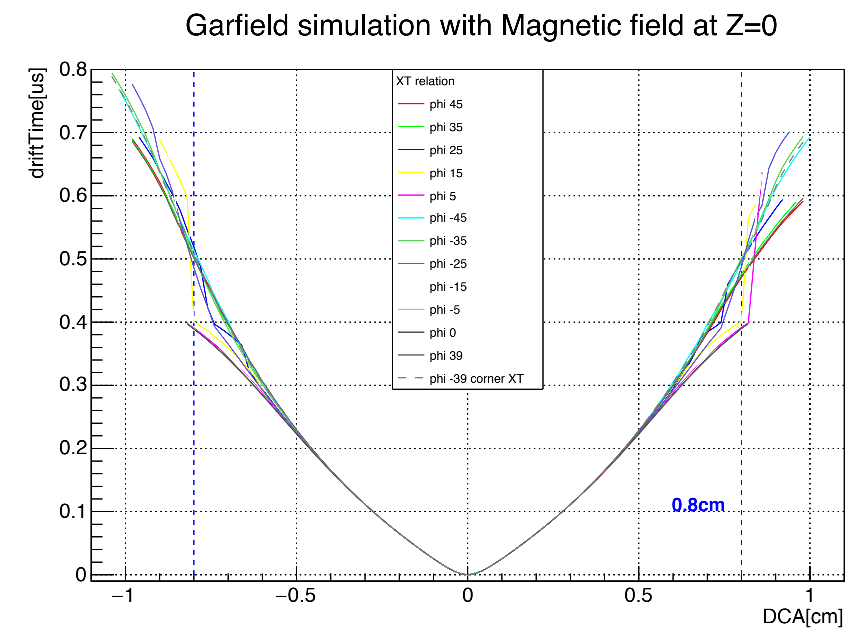


Figure 7.4: *Contours of electric field distribution calculated by* `Garfield` *for a cell of 1.6×1.6 cm^2, sense and field wires of $\phi 25$ and $\phi 126$ μm, and HV of 1800 V (top left), and the electric field distribution along the x-axis at $y = 0$ (top right). Electric field at surface of field wires as a function of the field wire diameter for HV of 1800 and 2300 V (bottom left), and that as a function of HV for the field wire diameter of 126 μm.*

Gas system

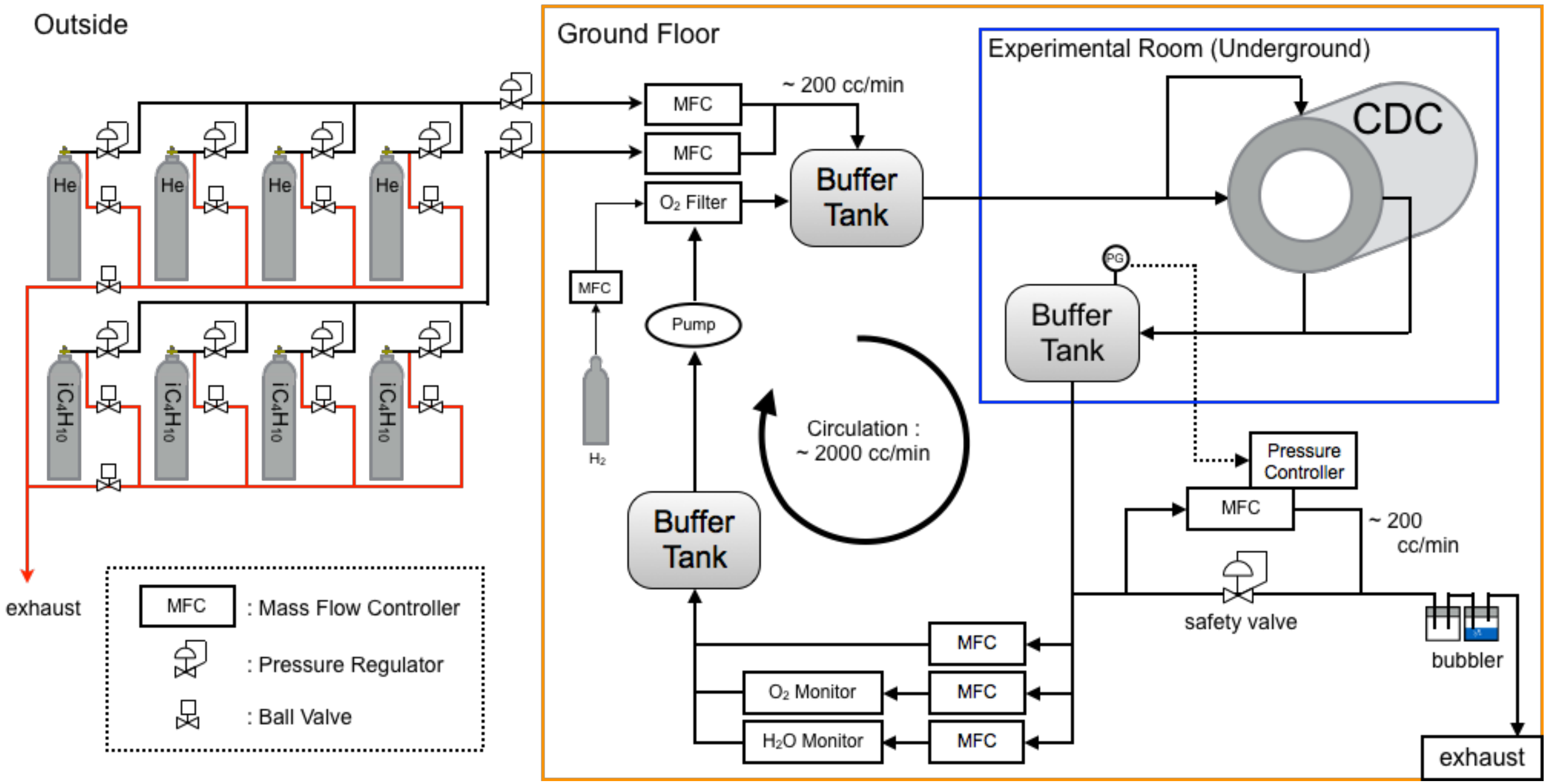
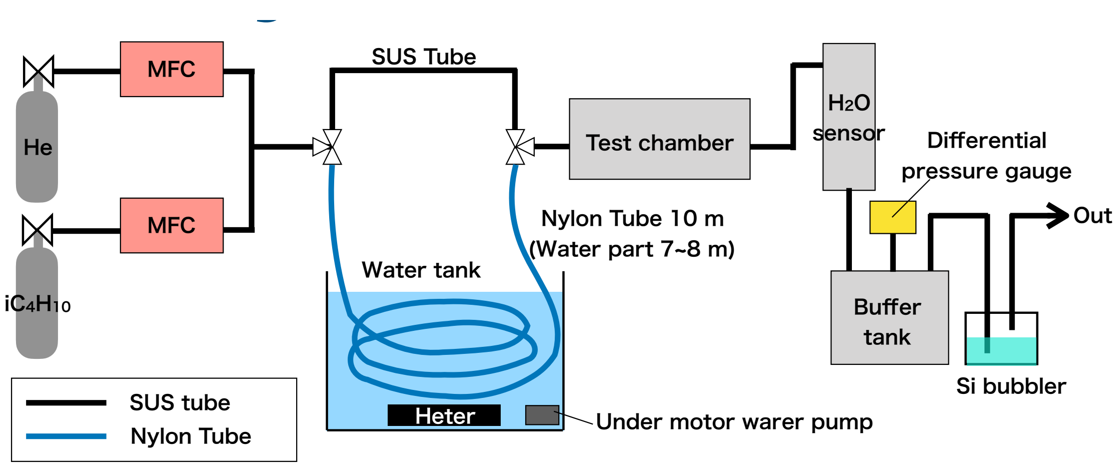
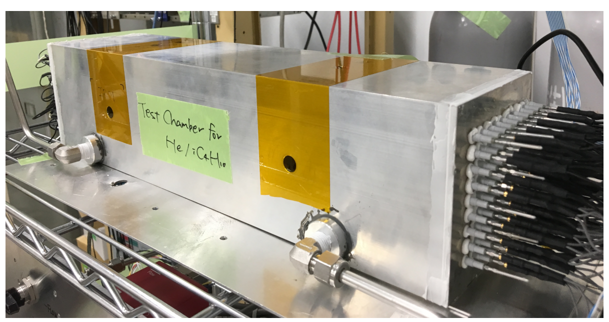


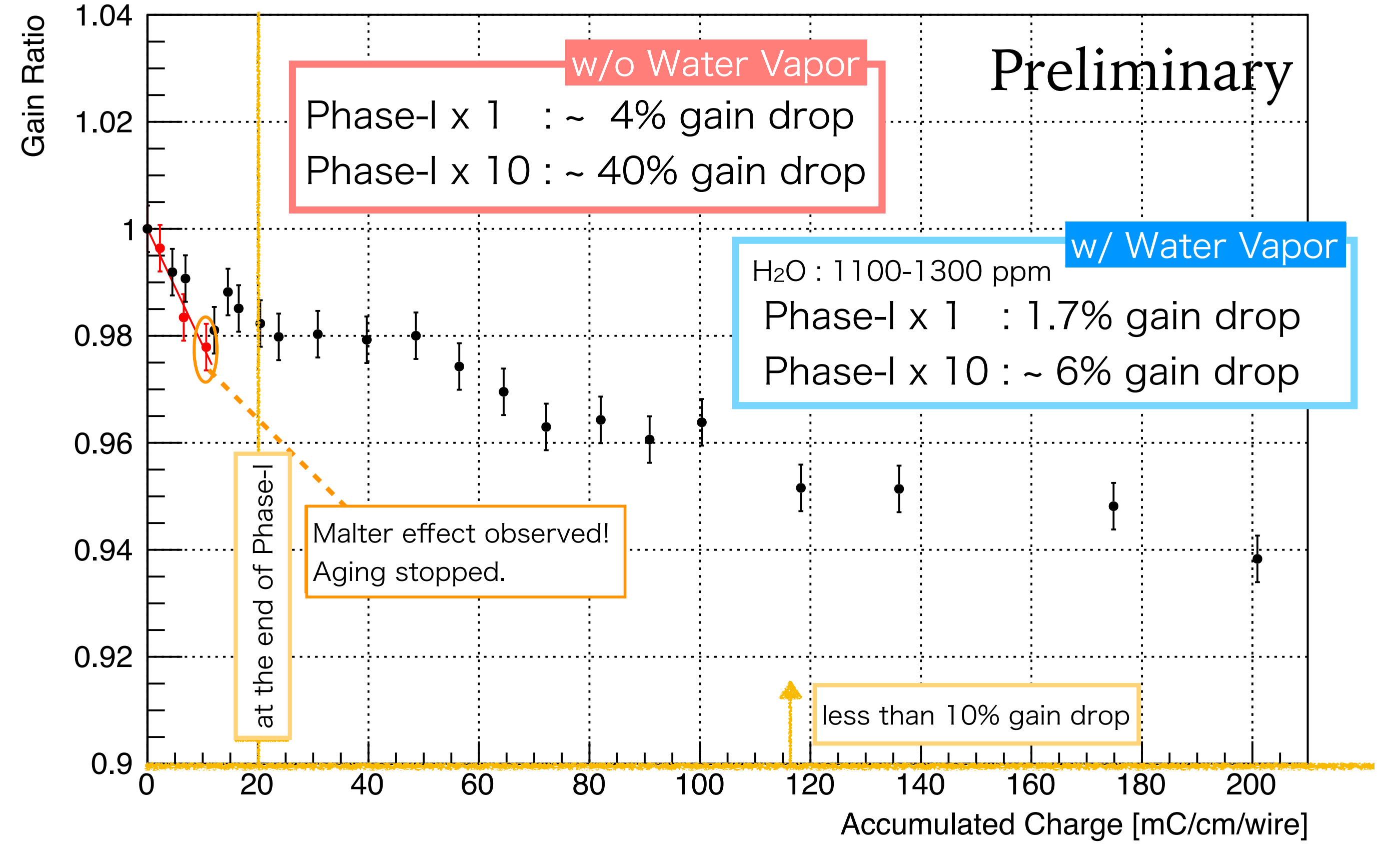
Figure 7.19: *Schematic view of the gas system for the CDC.*

Wire aging test

He:iC_4H_{10} (90:10)

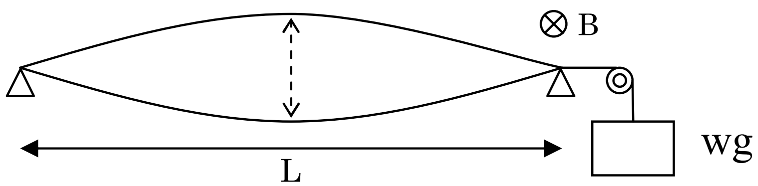






- Accumulated charge is predicted to be 20 mC/cm/wire for Phase-I.
- Wire aging effect was studied up to 200 mC/cm/wire.
- Without water vapor addition, Malter effect (discharge & large leak current) occurred around 20 mC/cm.
- With water vapor of 1100~1300 ppm, we could avoid Malter effect and gain drop was obtained to be 1.7 & 6% at 20 & 200 mC/cm, respectively. —> small enough

Wire tension assurance



Resonant Frequency: $f = \frac{1}{2L}\sqrt{\frac{wg}{\rho}},$

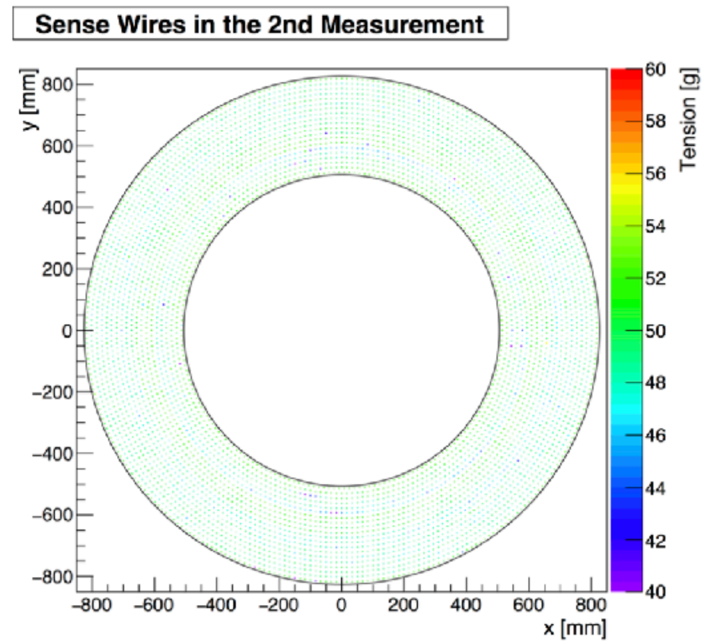
ρ = wire linear density

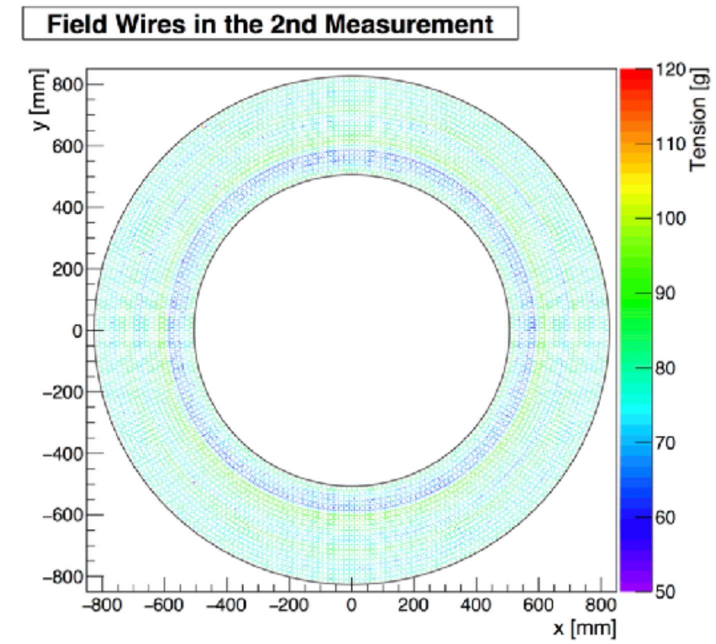
Nominal value	Material	Diameter	Tension	Sag
Sense	(Au-)W	25 μm	50 g	~50 μm
Field	Al	126 μm	80 g	~120 μm

L = 1477~1593 mm

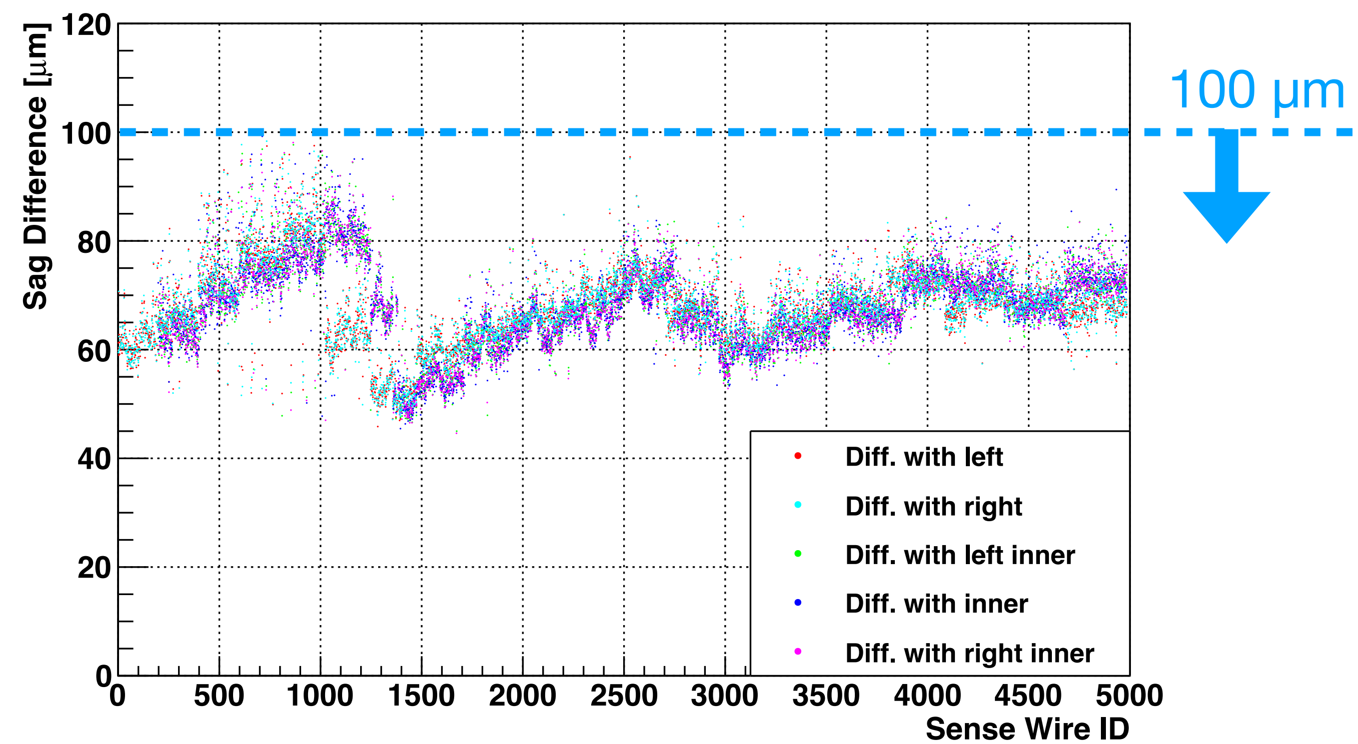
Gravitational Sag: $s = \frac{\rho L^2}{8wg}.$

Criteria
- Sag for sense wire < 70 μm
- Sag difference with neighbor wires < 100 μm





Sag differences between a sense wire and surrounding field wires



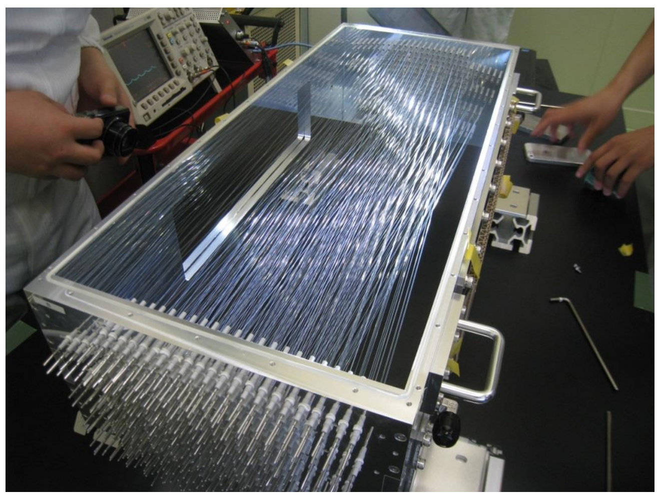
After replacing bad wires, all the wires satisfy the criteria.

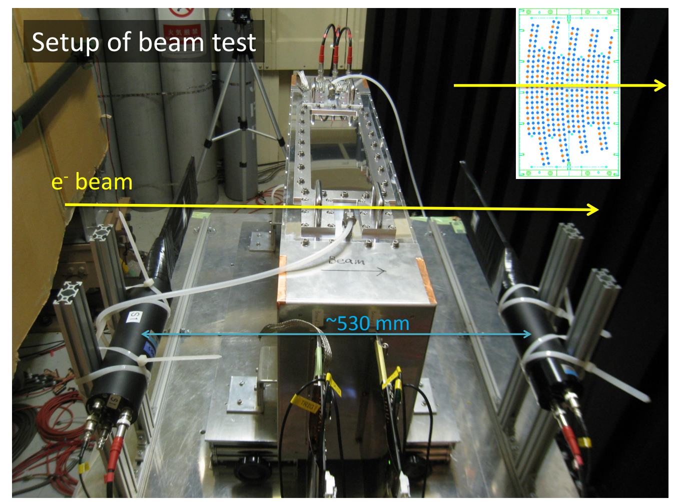
Prototype tests

- Prototype chambers are tested by using electron beams with 3 types of gas mixtures.
- $He:iC_4H_{10}$ (90:10) & $He:C_2H_6$ (50:50) show good performance.

Gas parameters

	$He:C_2H_6$ (50:50)	$He:iC_4H_{10}$ (90:10)	$He:CH_4$ (80:20)
Rad. Len. [m]	630	1310	2166
e/ion pair [/cm]	60	29	17
drift velocity [cm/us]	~4.0	~2.4	~2.8
	(Belle/Belle-II)	(KLOE)	





Drift Velocity

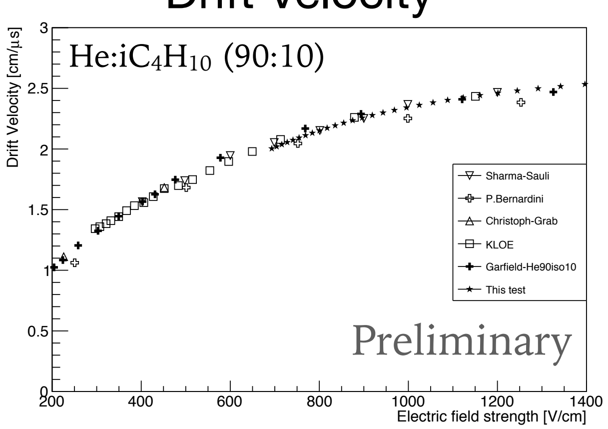


Figure 8: Drift velocity versus the electric field for $He-iC_4H_{10}(90/10)$ by comparing with Garfield++ simulation and experiment of C.Grab[11], P.Bernardini[12], Sharma-Sauli[13] and KLOE[4]

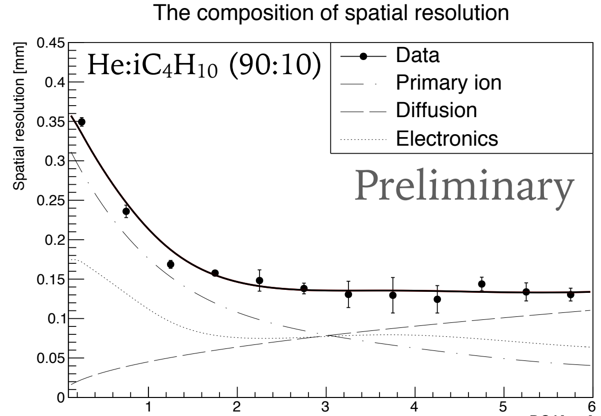


Figure 9: Spatial resolution as a function of drift distance distance for $He-iC_4H_{10}(90/10)$ at 1800 V. The dot-dashed line shows primary ionisation contribution. The dashed line shows the diffusion contribution. The dotted line shows the electronics contribution. The solid line shows fitted curve.

Gas Gain

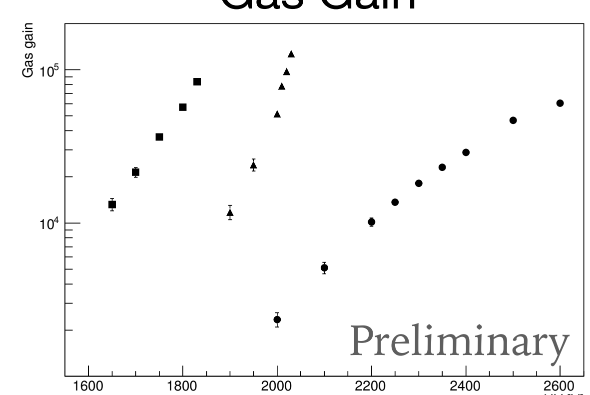
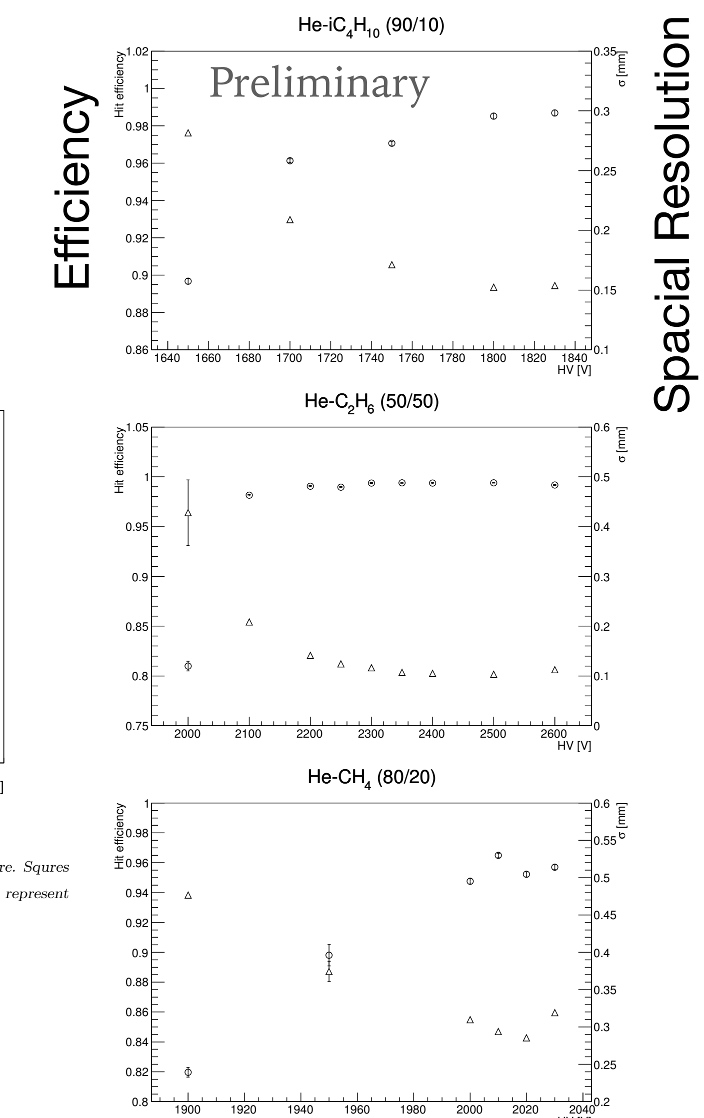
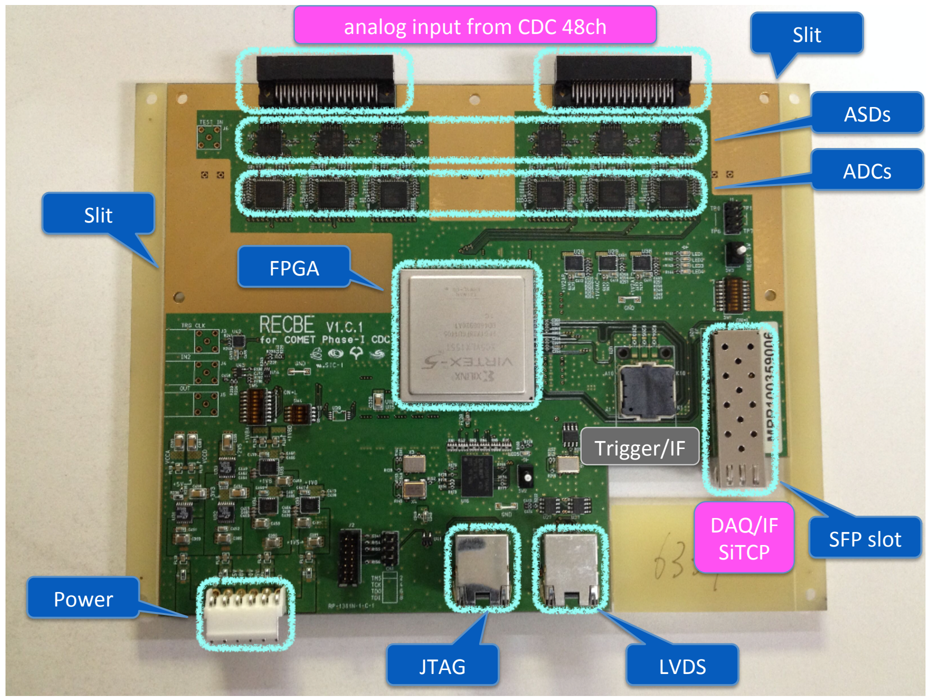


Figure 11: Relation between gas gain and high voltage for three types of gas mixture. Squres represent $He-iC_4H_{10}(90/10)$. Full circles represent $He-C_2H_6(50/50)$. Triangles represent $He-CH_4(80/20)$.

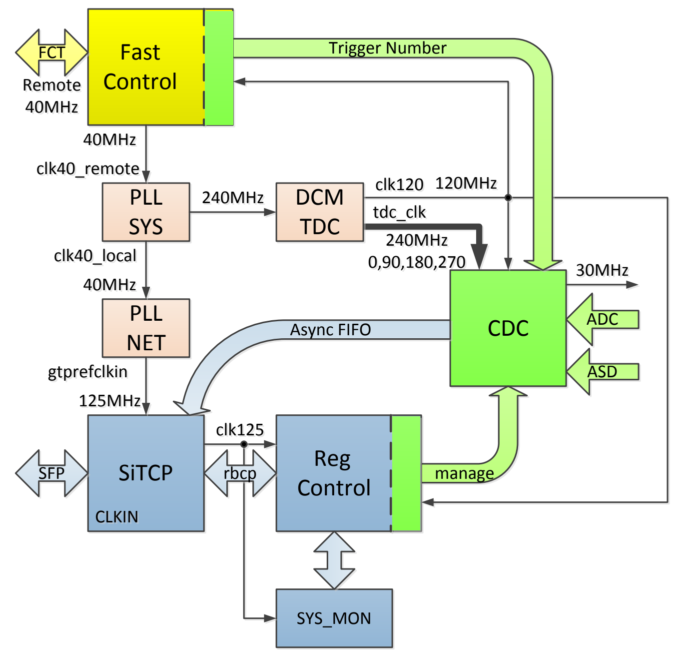


Frontend readout electronics



Frontend readout board: **RECBE**

(= Readout Electronics for CDC for Belle-2 Experiment)



Firmware design

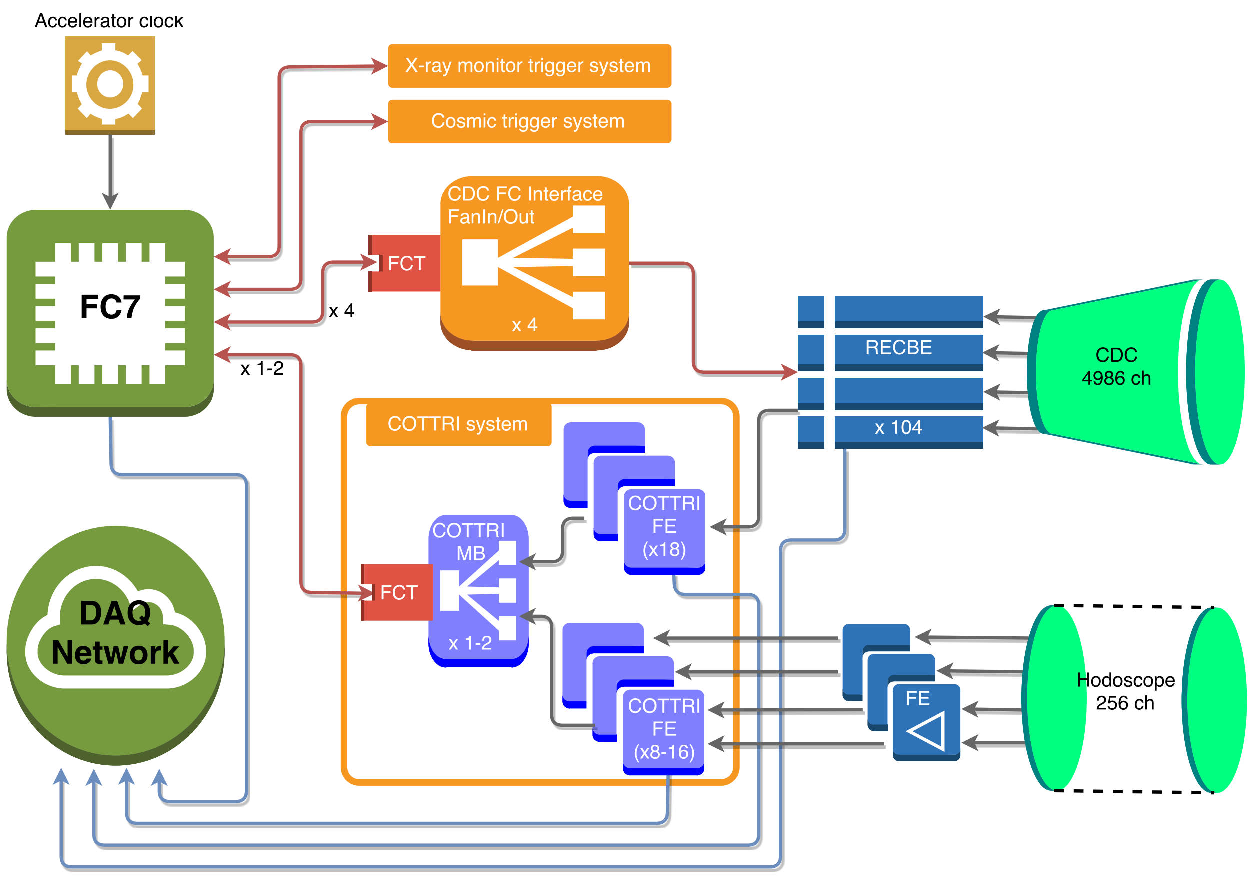
TDC: 960 MHz
ADC: 30 MHz sampling

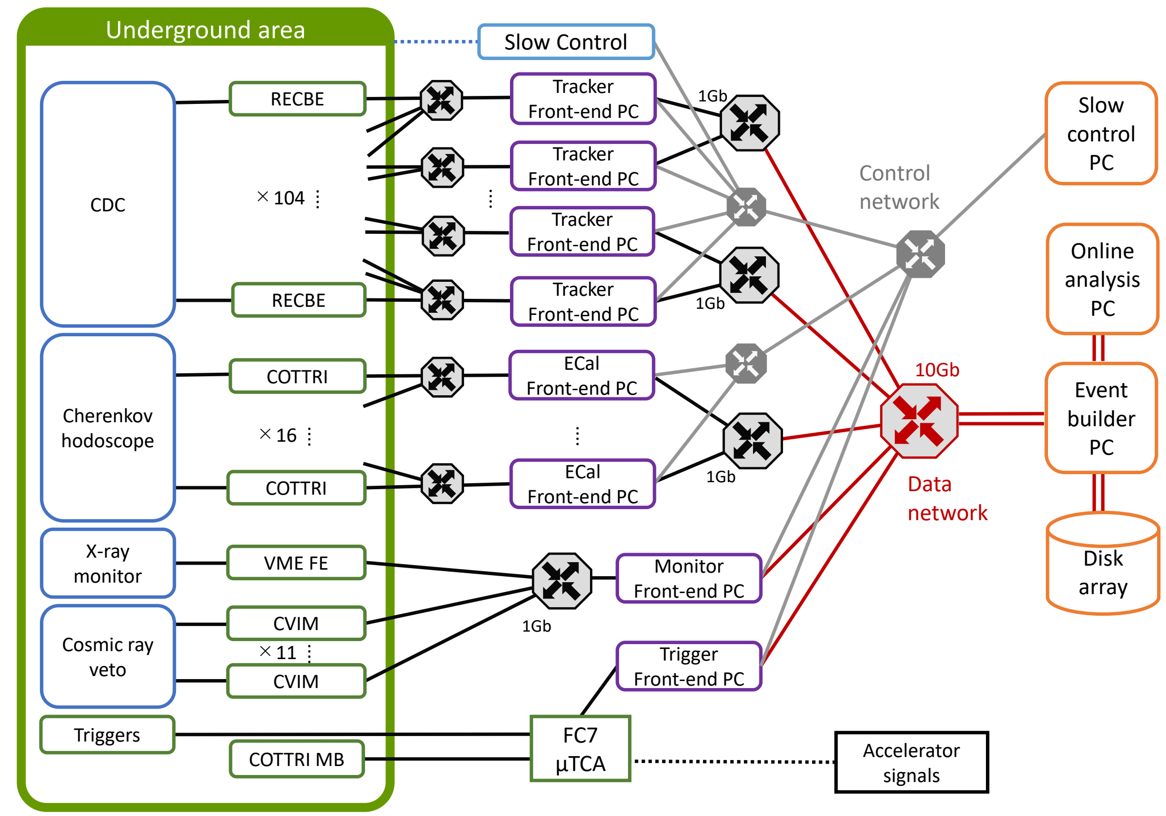
All 128 RECBEs were already fabricated and QA was done by IHEP group.

- Radiation tolerance against gamma & neutrons has been studied.
  - Regulators & SFP could survive up to 1.8 & 1.1 kGy, respectively. —> acceptable
  - FPGA URE rate = 4/hour for 104 RECBEs.

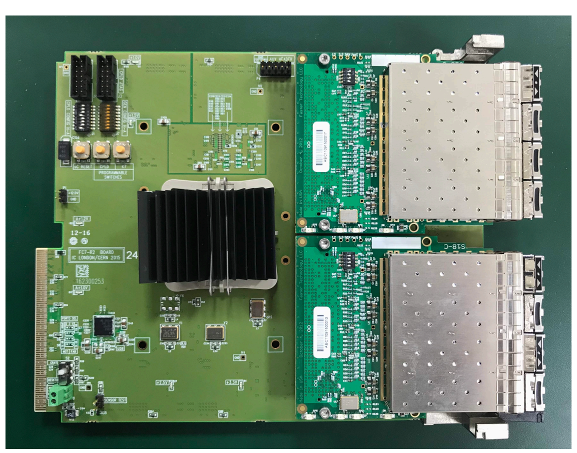
 # Predicted dose is 0.1~0.2 kGy for Phase-1

Trigger & DAQ system

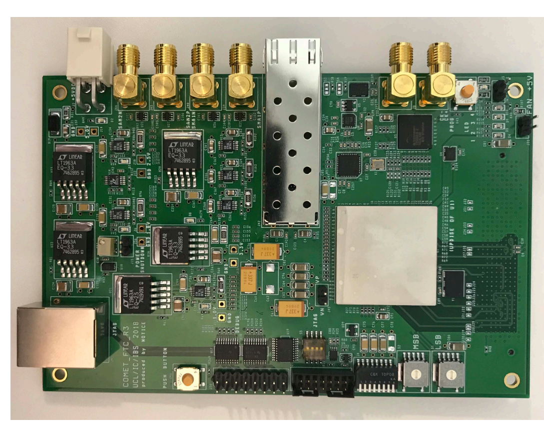




FC7



FCT



I/F board for FCT & RECBE

Sensitivity & Background

@ Phase-I

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}},$$

$$\begin{aligned} B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) &= 3 \times 10^{-15} \quad \text{(as SES) or} \\ &< 7 \times 10^{-15} \quad \text{(as 90 \% C.L. upper limit).} \end{aligned}$$

Table 12.8: *Summary of the estimated background events for a single-event sensitivity of* 3×10^{-15} *in COMET Phase-I with a proton extinction factor of* 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.