# Construction and performance tests of the COMET CDC

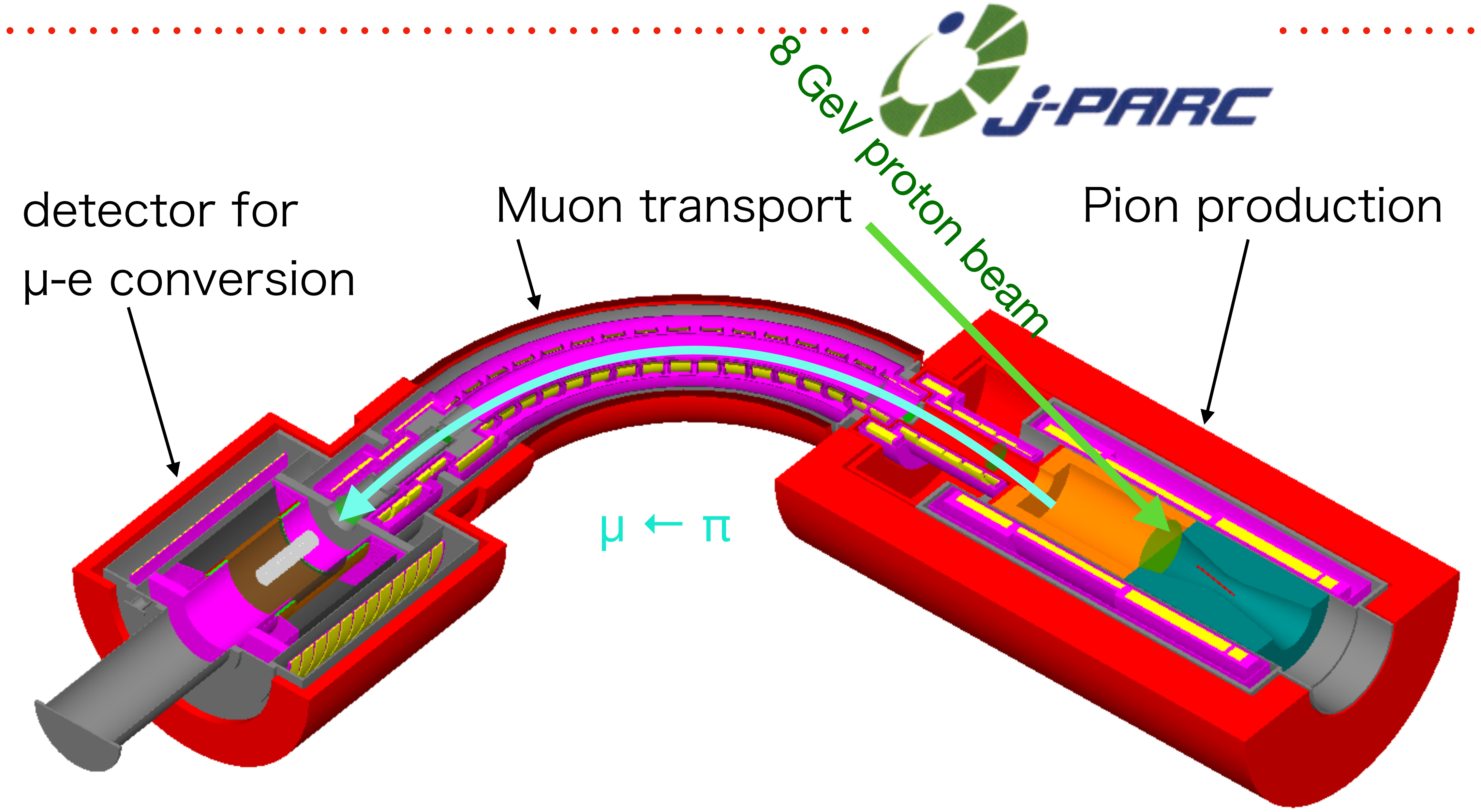
Manabu Moritsu (KEK, Japan)
*On behalf of the COMET Collaboration*

39th International Conference on High Energy Physics (ICHEP2018)
7th July 2018, COEX, Seoul, Korea

# μ–e conversion & COMET

COMET talk by D.Grigoriev
15:40, 7 July @102

COMET Phase-I Layout




- The COMET experiment at J-PARC searches for the neutrinoless coherent transition of a muon to an electron in the field of an aluminum nucleus, which violates the lepton flavor conservation and has never been observed yet thus far.

$$\mu^- N \to e^- N$$

- The conversion rate is predicted to be enhanced in new physics models beyond the Standard Model, while the process is extremely suppressed in the Standard Model.
- The goal of the COMET is to explore the $\mu$-e conversion with single event sensitivity of $3\times10^{-15}$ and $3\times10^{-17}$ in Phase-I and Phase-II, respectively, which is 100 and 10,000 times better than the current limit.
- COMET Phase-I:
  - J-PARC 8GeV-3.2 kW proton beam → Capture Solenoid → Transport Solenoid (90-deg bend) —> Cylindrical Detector System

# Signal & background

- The signal of the $\mu$-e conversion is **~105 MeV** mono-energetic electrons,

$$E_{\mu e} = m_\mu - B_\mu - E_{\text{rec}} = 104.97 \text{ MeV for Al}$$

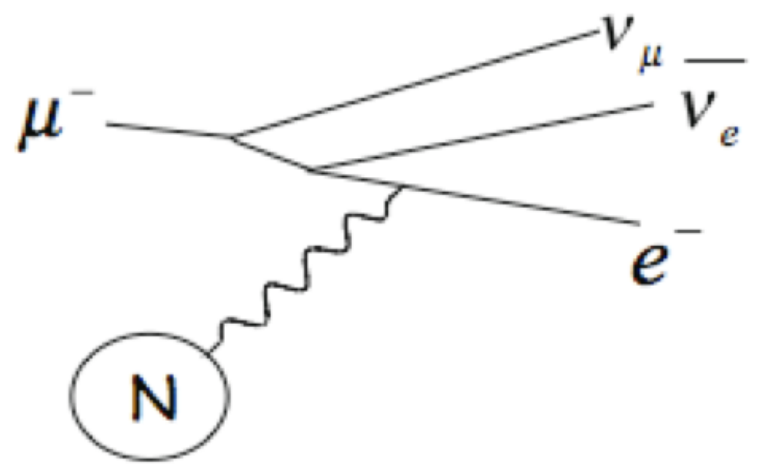
- while the backgrounds are
  1. Decay-in-orbit (DIO) electrons
  2. Prompt beam-related BG
  3. Cosmic-ray induced BG.

# Signal & background

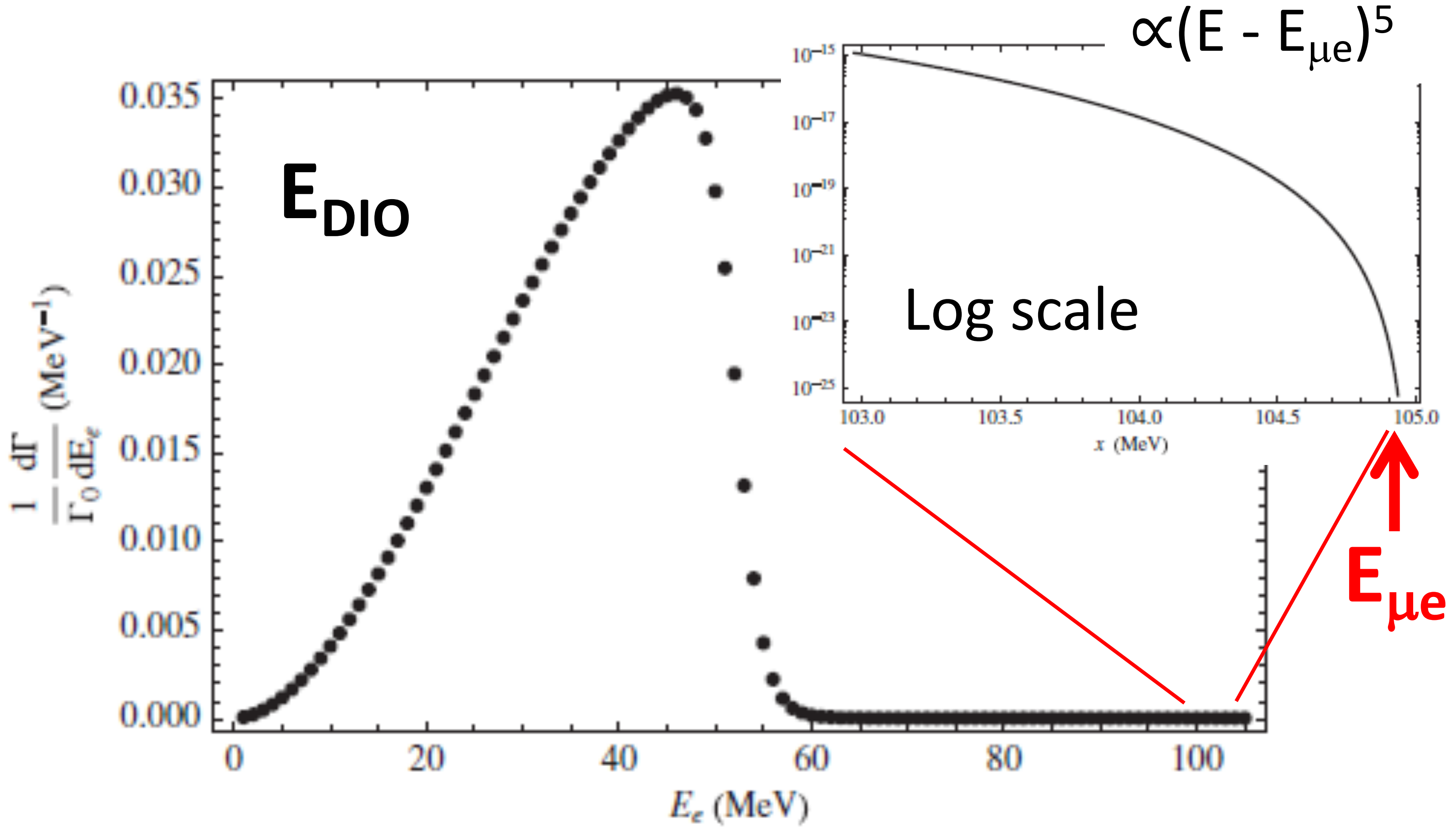
- The signal of the $\mu$-e conversion is **~105 MeV** mono-energetic electrons,

$$E_{\mu e} = m_\mu - B_\mu - E_{\text{rec}} = 104.97 \text{ MeV for Al}$$

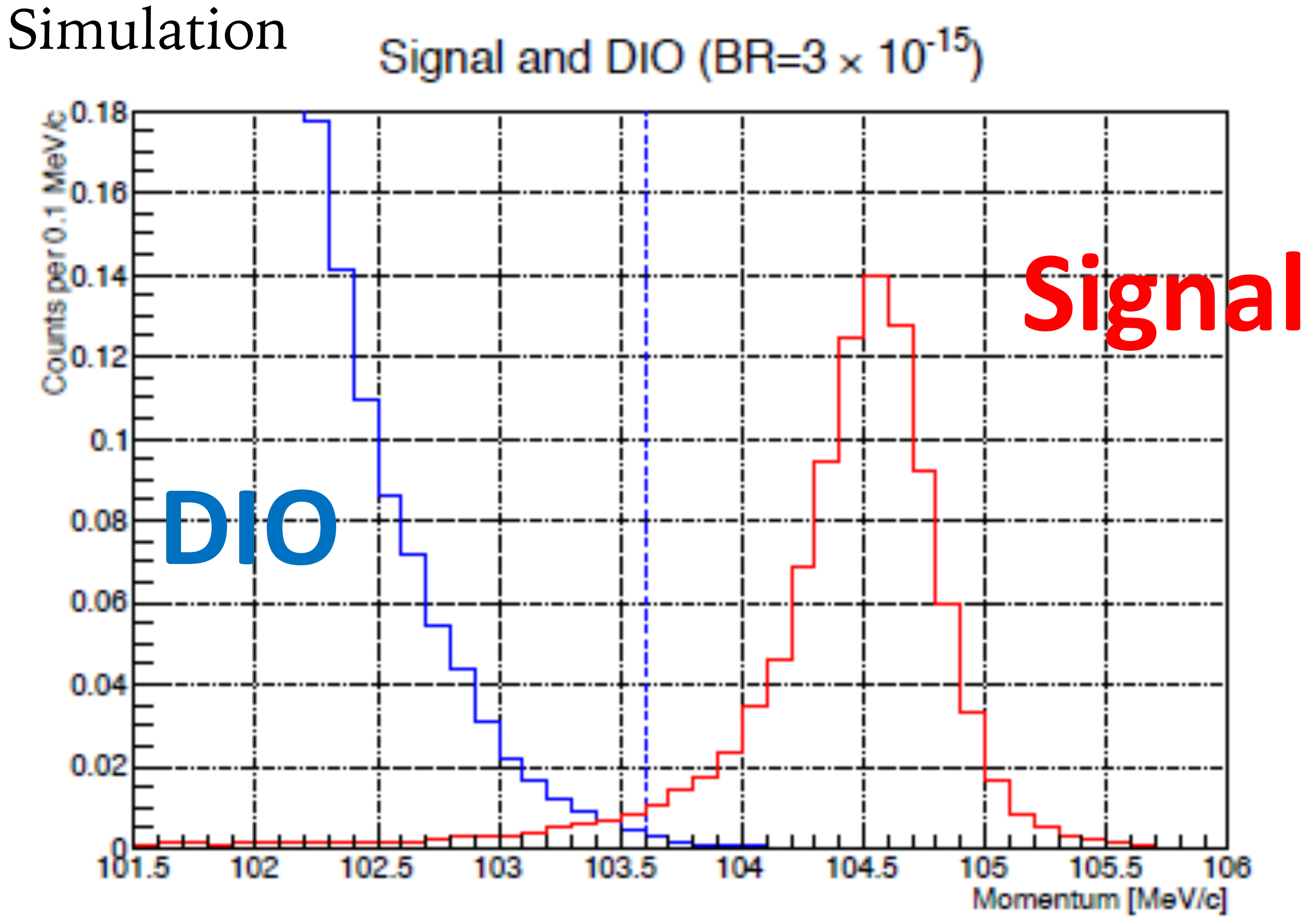
- while the backgrounds are
  1. Decay-in-orbit (DIO) electrons ← *Inevitable physical BG*
  2. Prompt beam-related BG
  3. Cosmic-ray induced BG.
- In order to distinguish the signal from the background, good momentum resolution of **200 keV/c** is required.




Muon Decay in Orbit (DIO)



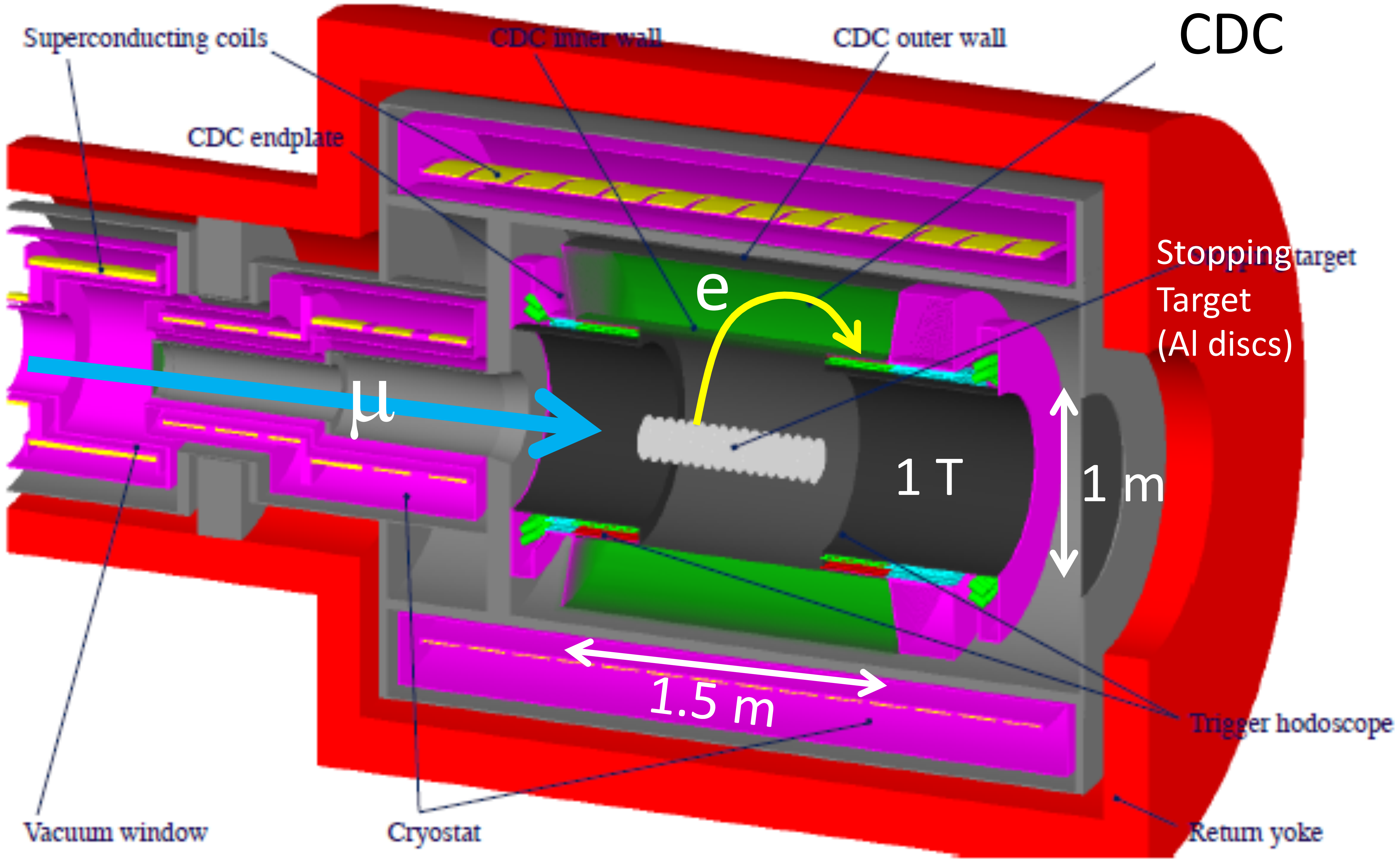

Simulation

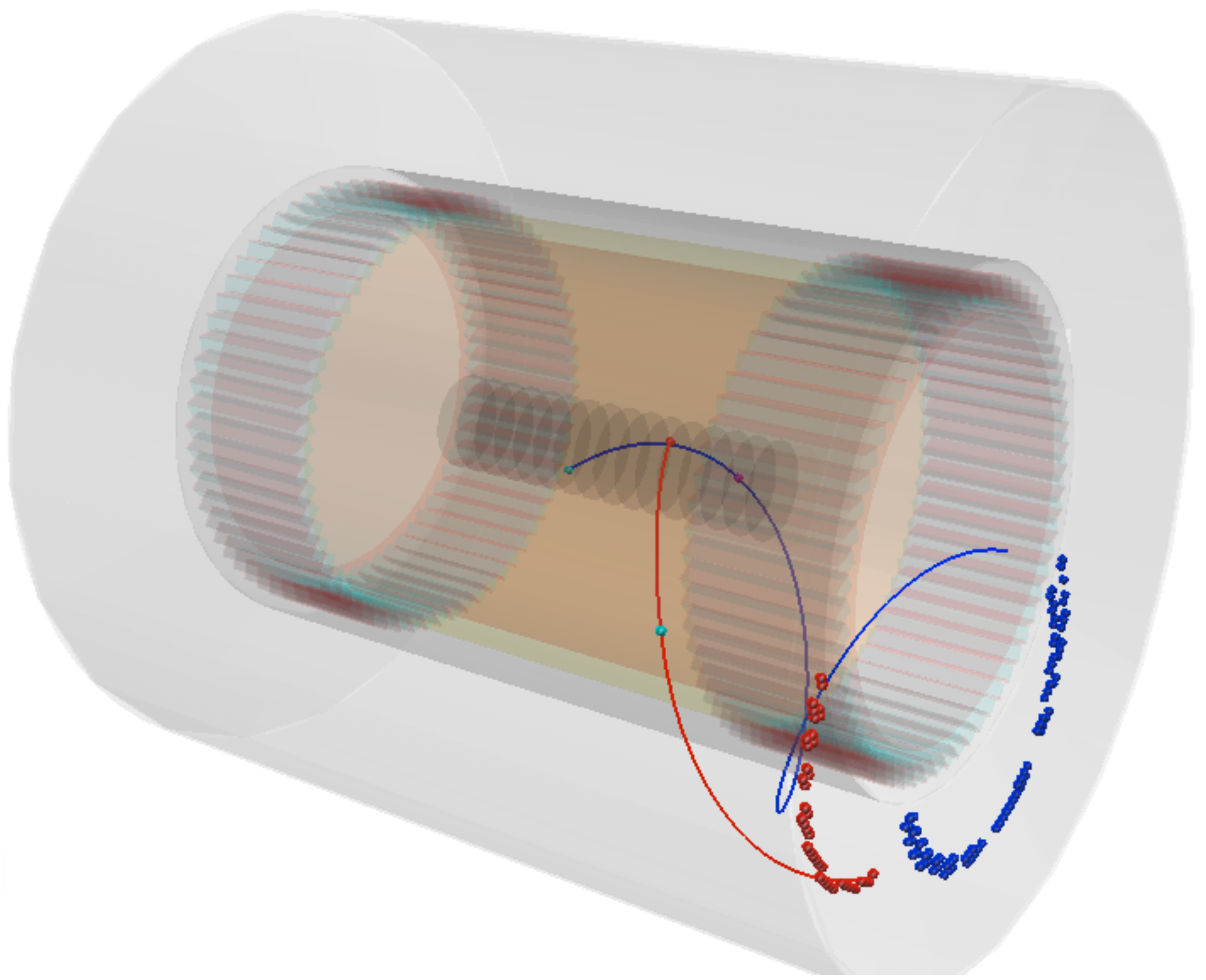



$E_{DIO}$ can have a high-energy tail, which is in principle reach $E_{\mu e}$.

# COMET CDC

- In the COMET Phase-I, the converted electrons, which possess monochromatic momentum of 105 MeV/c, are detected with a **cylindrical drift chamber (CDC)** in a solenoidal magnetic field of **1 T**.
- Trigger signals are issued by a combination of **scintillation & Cherenkov hodoscopes** placed at inner side both upstream & downstream of CDC.
- In this low momentum region around 105 MeV/c, momentum resolution is dominated by the multiple-scattering effect.
- In order to realize the excellent resolution of **200 keV/c**, low-mass tracking region is essential.
  - **He:i-$C_4H_{10}$ (90:10)** gas mixture for CDC
  - **Al field wires** with 126-$\mu$m diameter
  - Thin CFRP inner wall with **0.5 mm**



*#Note: target volume is filled with He gas.*

*Al target consists of 17 discs with 100-mm radius, 0.2-mm thickness, & 50-mm spacing.*

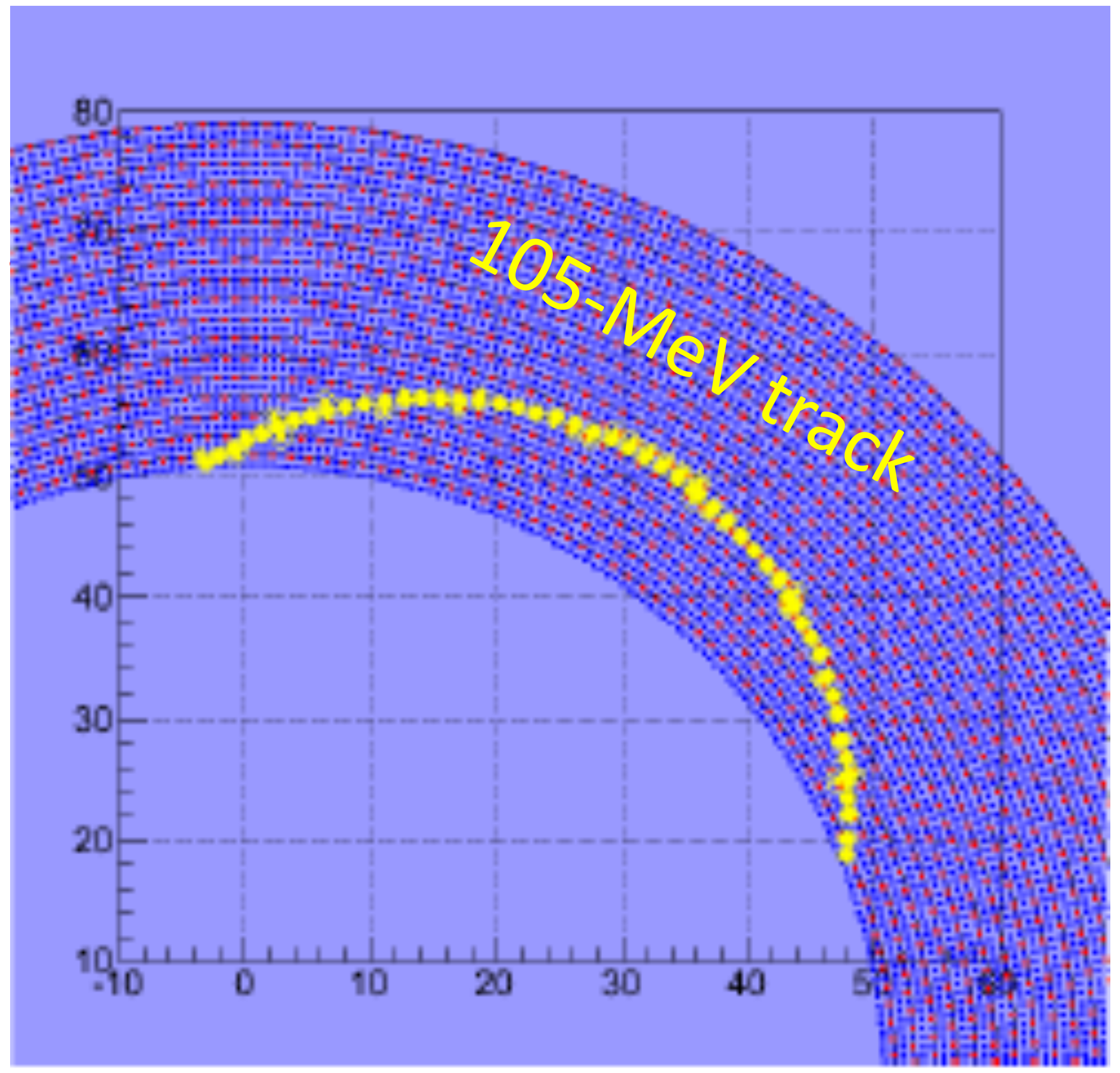
# Design of CDC

Feature of CDC Specification:

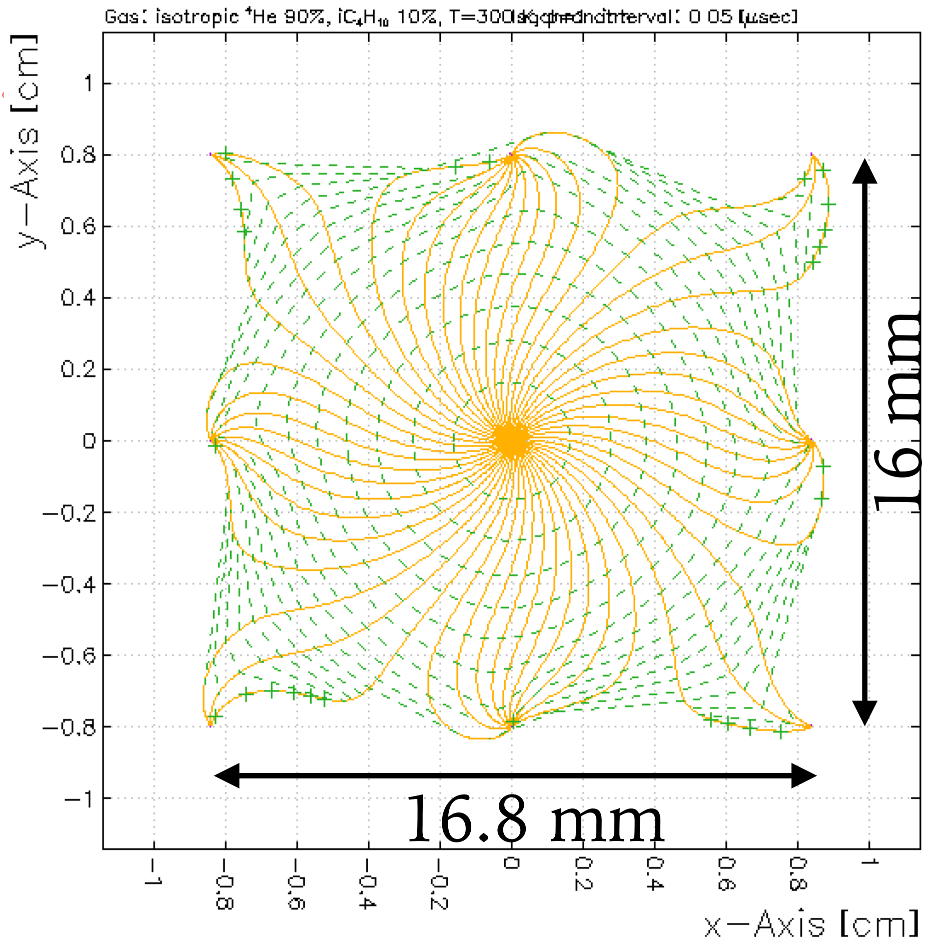
- **Large inner diameter of ~1 m**
  - Most of DIO electrons (< 60 MeV/c) do not reach CDC
- Cell structure
  - **Alternating all stereo layer**: 64~75 mrad
    - for good resolution in longitudinal direction

Table 7.1: Main parameters of the CDC.

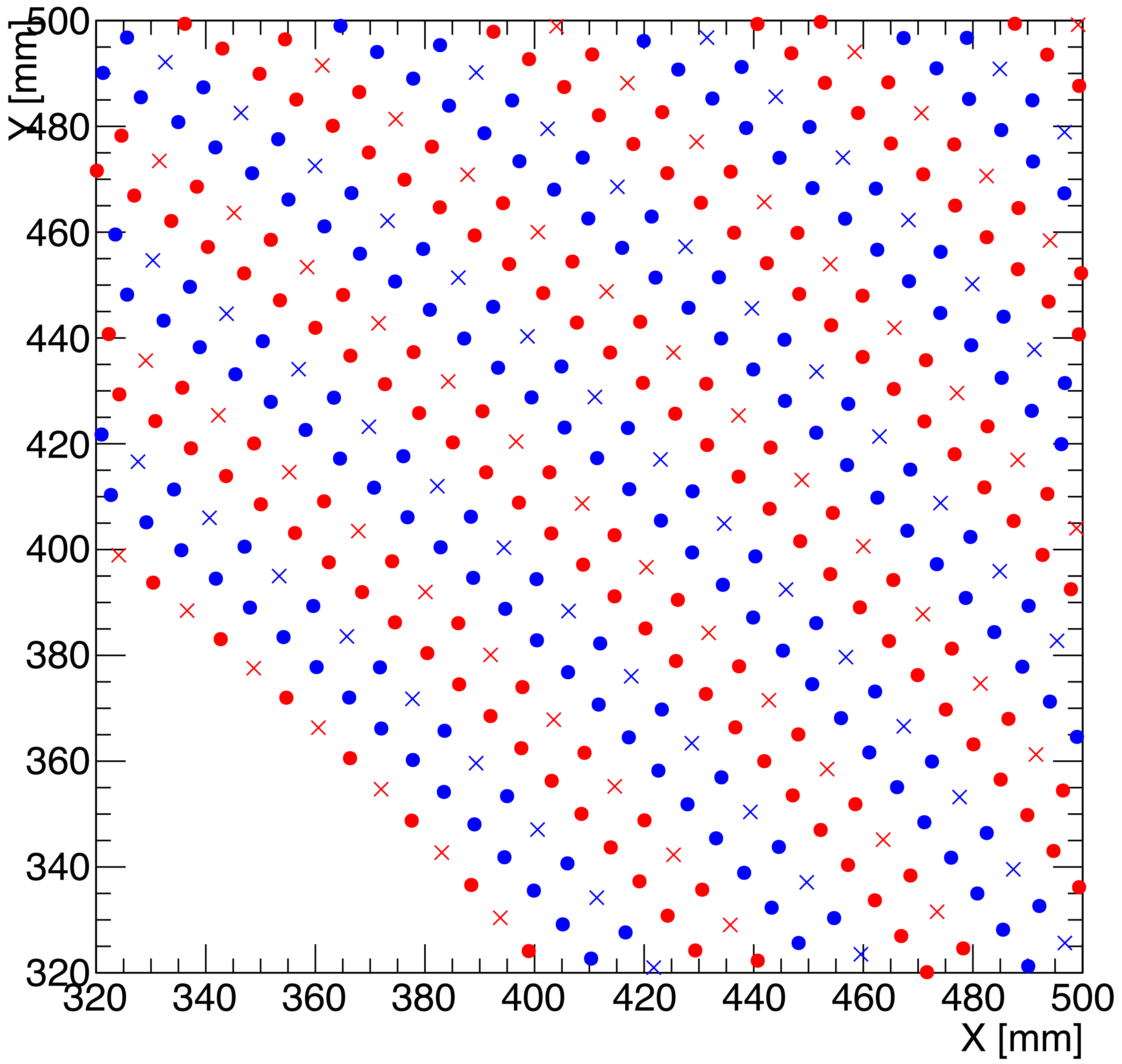
| | | |
|---|---|---|
| Inner wall | Length | 1495.5 mm |
| | Radius | 496.0~496.5 mm |
| | Thickness | 0.5 mm |
| Outer wall | Length | 1577.3 mm |
| | Radius | 835.0~840.0 mm |
| | Thickness | 5.0 mm |
| Number of sense layers | | 20 (including 2 guard layers) |
| Sense wire | Material | Au plated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




Electron drift lines



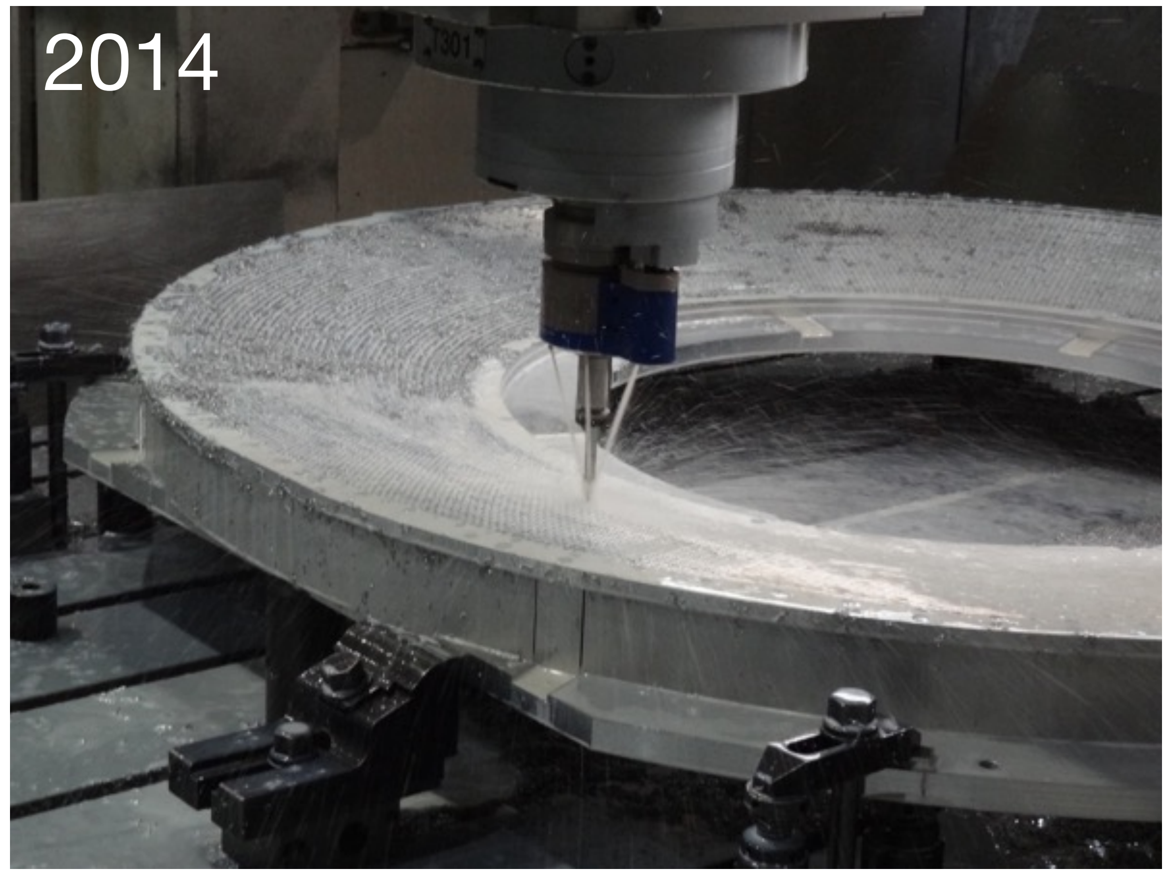

Z=0




× sense wire
• field wire

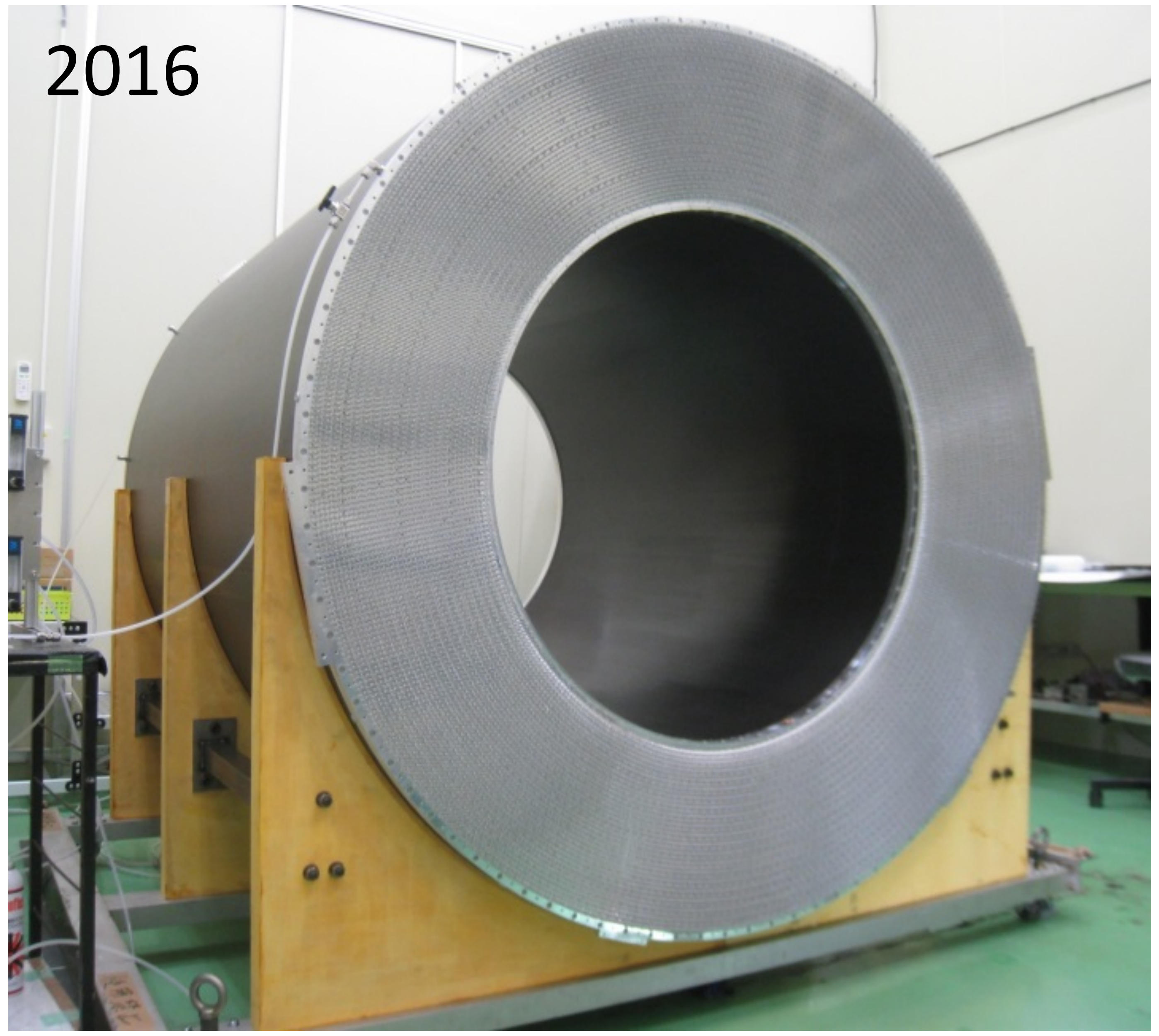
Stereo angle:
+ −

# Construction of CDC

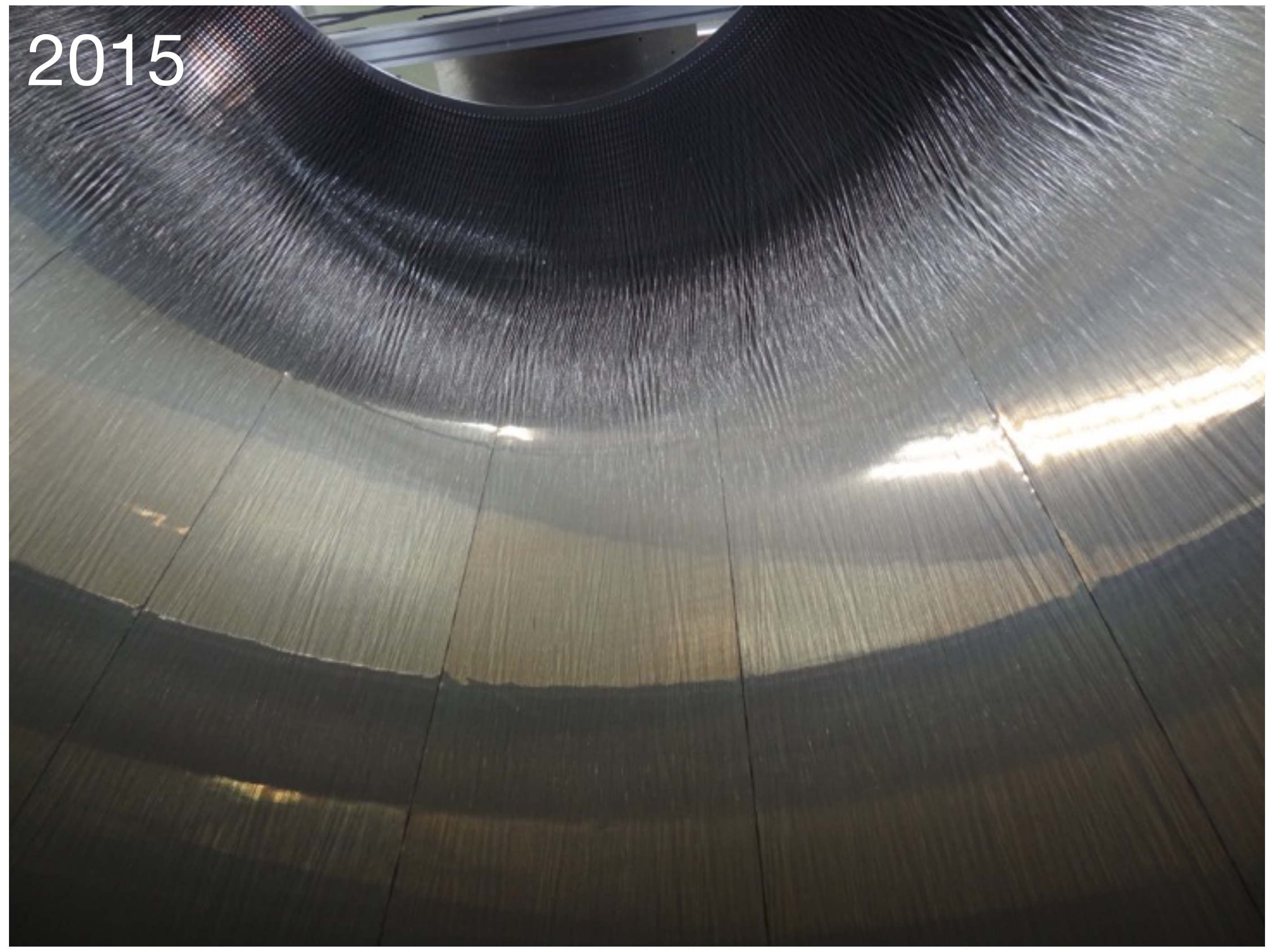



Drilling holes on endplates
with precision of 50 $\mu$m

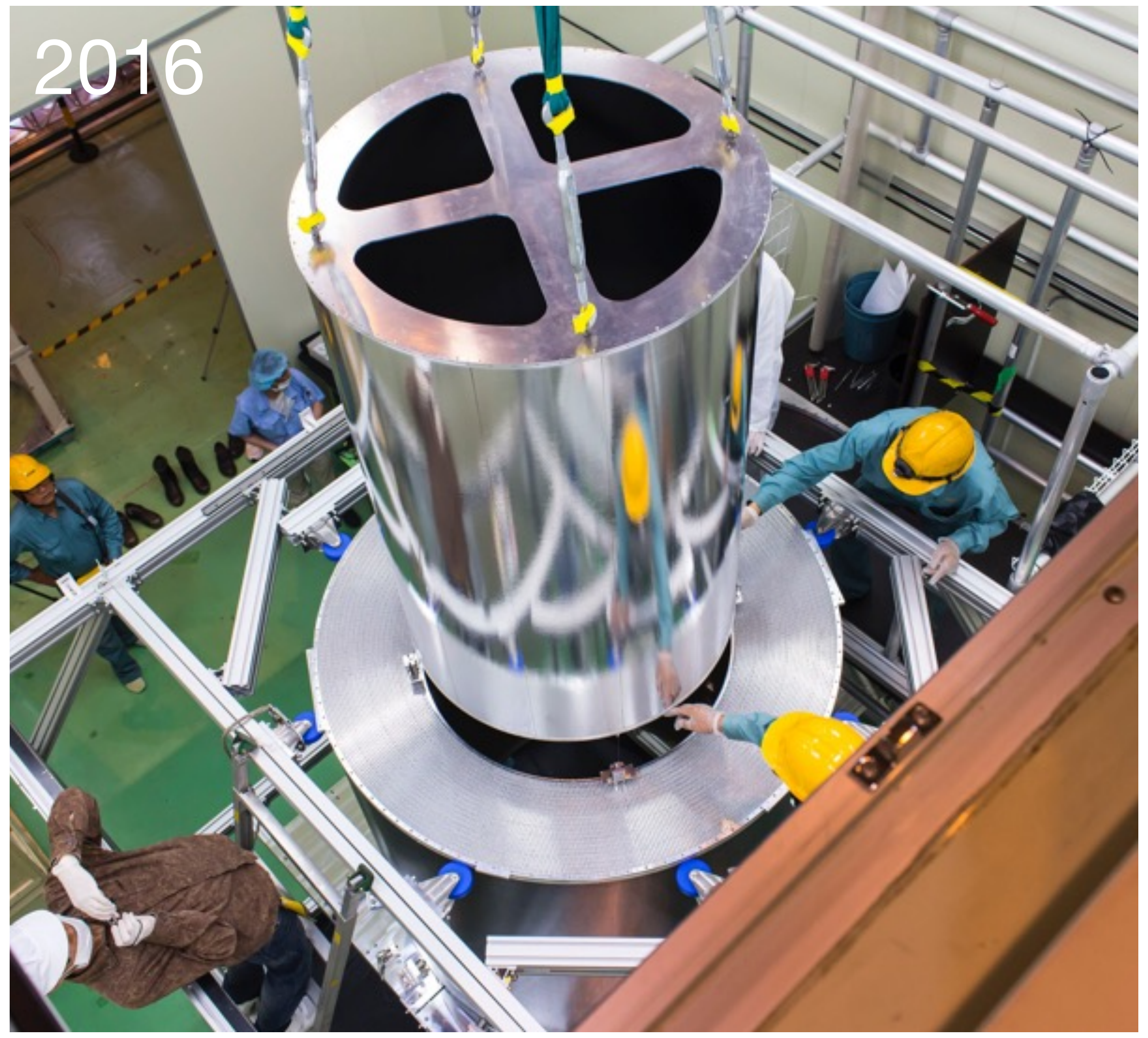

Outer structure was transported to a KEK assembly hall,
and set on a wire stringing cradle.




Completion of COMET CDC

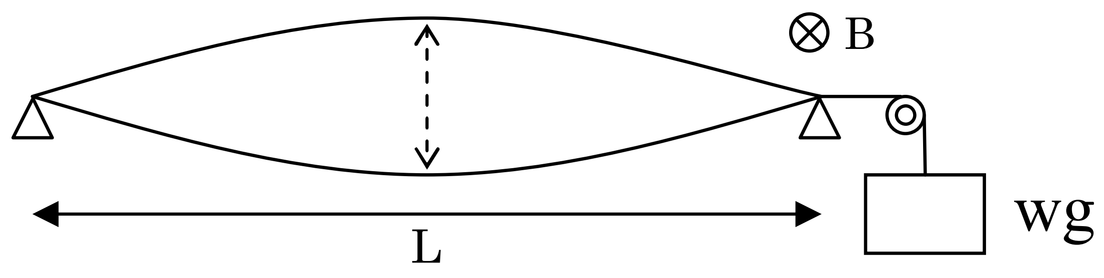



Wire stringing and tension measurement
for 19,548 wires were carried out in a half year.




Installation of inner wall
made of 0.5-mm thick CFRP

# 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 $\mu$m | 50 g | $\sim$50 $\mu$m |
| Field | Al | 126 $\mu$m | 80 g | $\sim$120 $\mu$m |

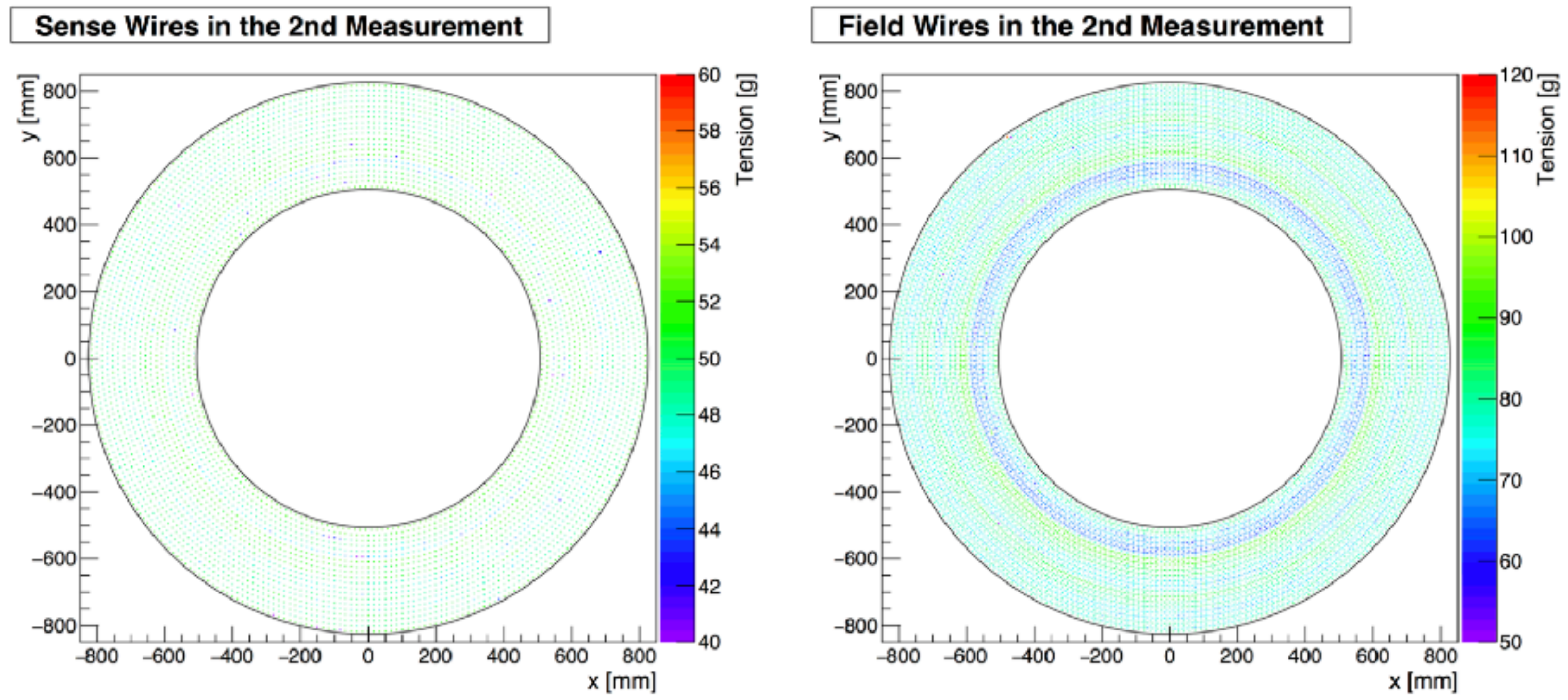
L = 1477~1593 mm

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

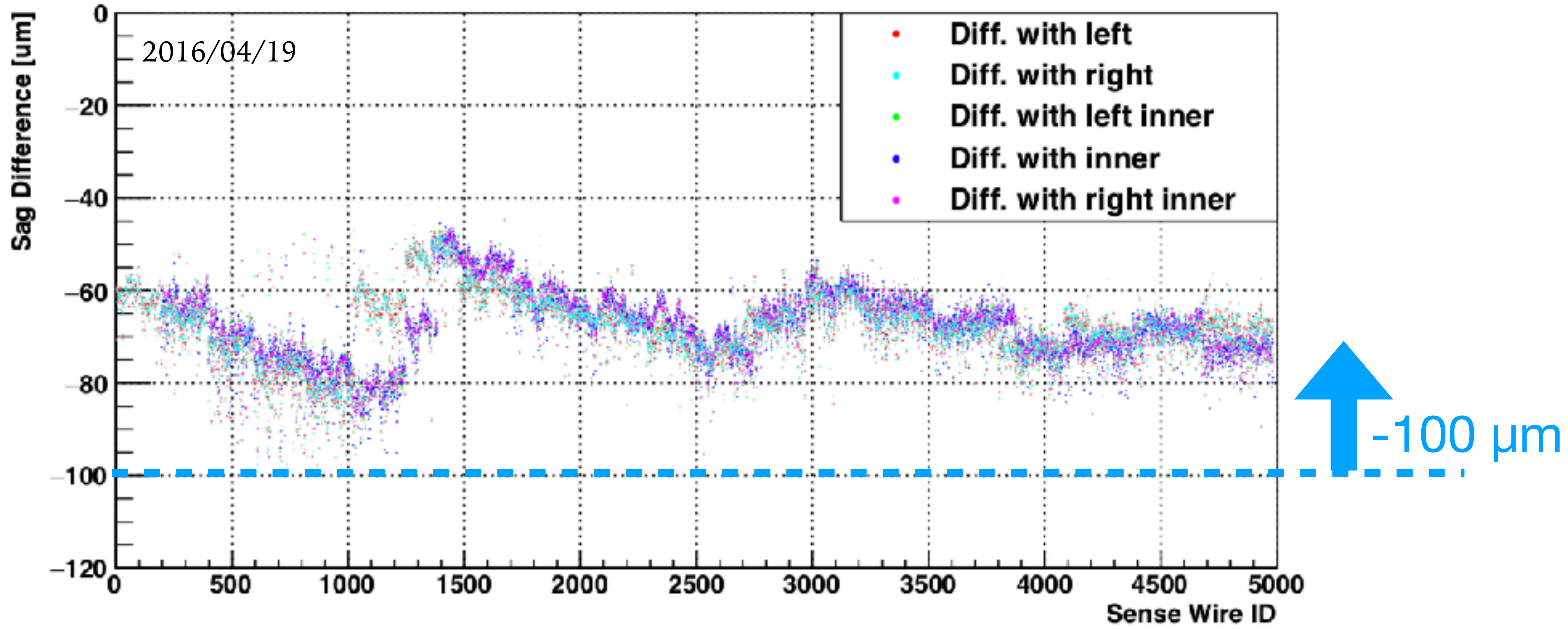
**Criteria**

- Sag for sense wire < 70 $\mu$m
- Sag difference with neighbor wires < 100 $\mu$m

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



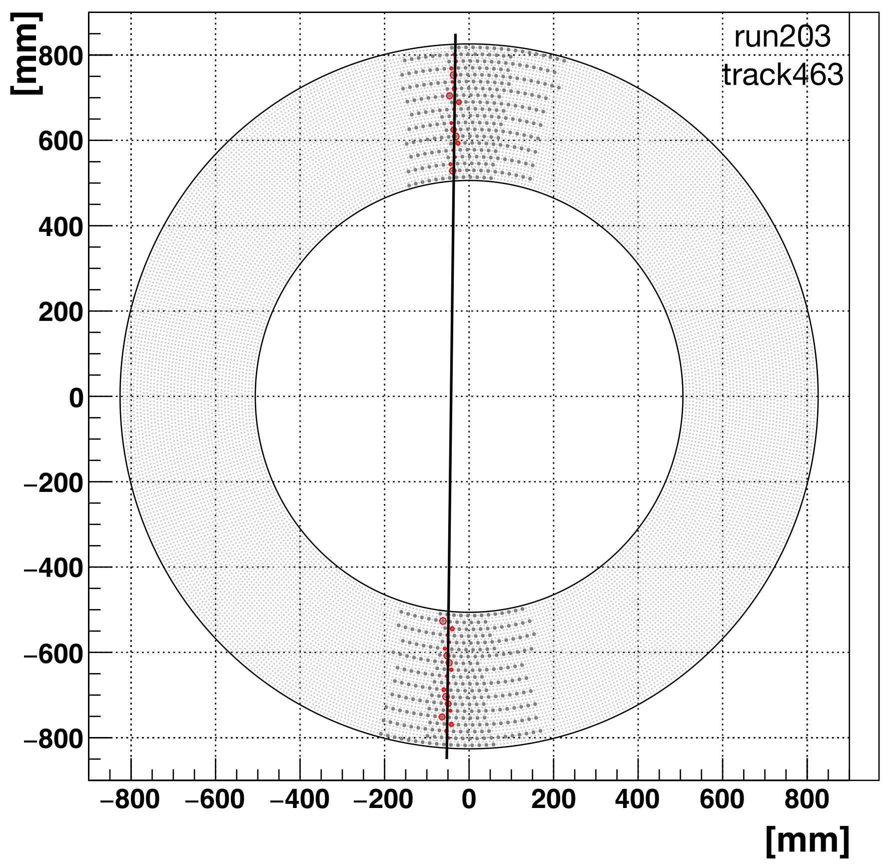

(b) Sag differences between a sense wire and surrounding field wires



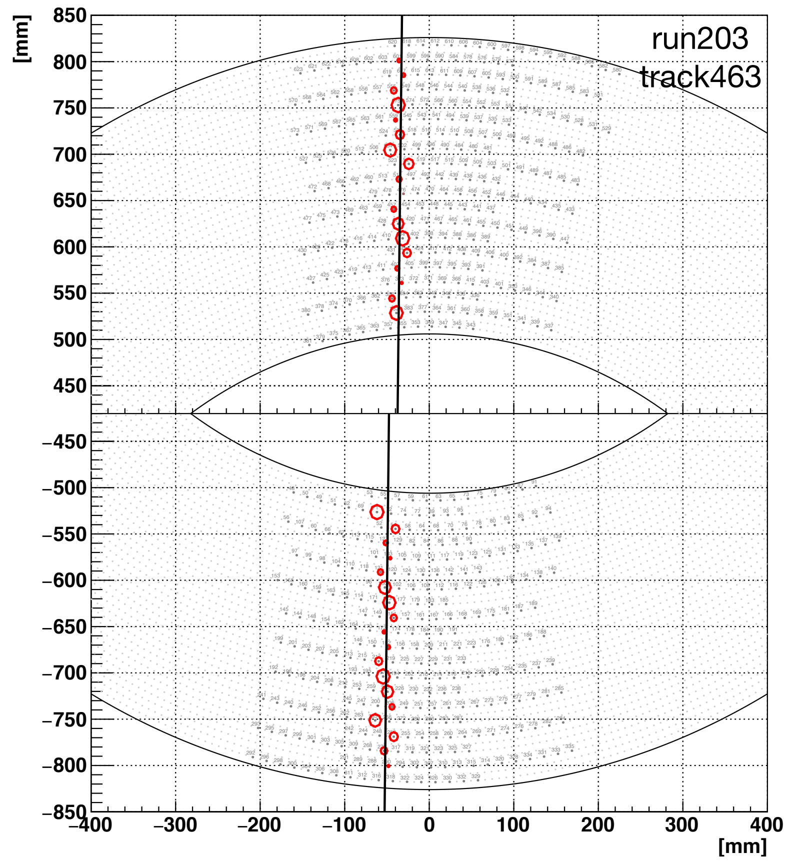
# Performance tests

- CDC performance tests using cosmic rays are being carried out with step-by-step upgrade of readout & surrounding systems as well as analysis scheme.
- We have obtained spacial resolution of **170 $\mu$m** & efficiency of **95%** so far.
- The performance tests will be continued in this year to precisely investigate whole region of the CDC.

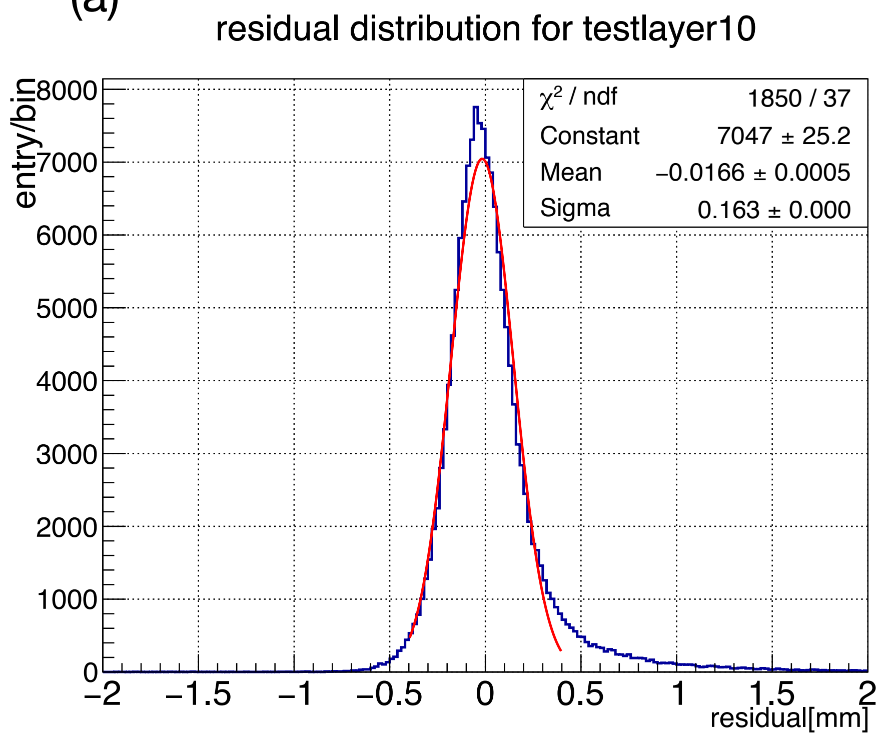
(a) Event Display



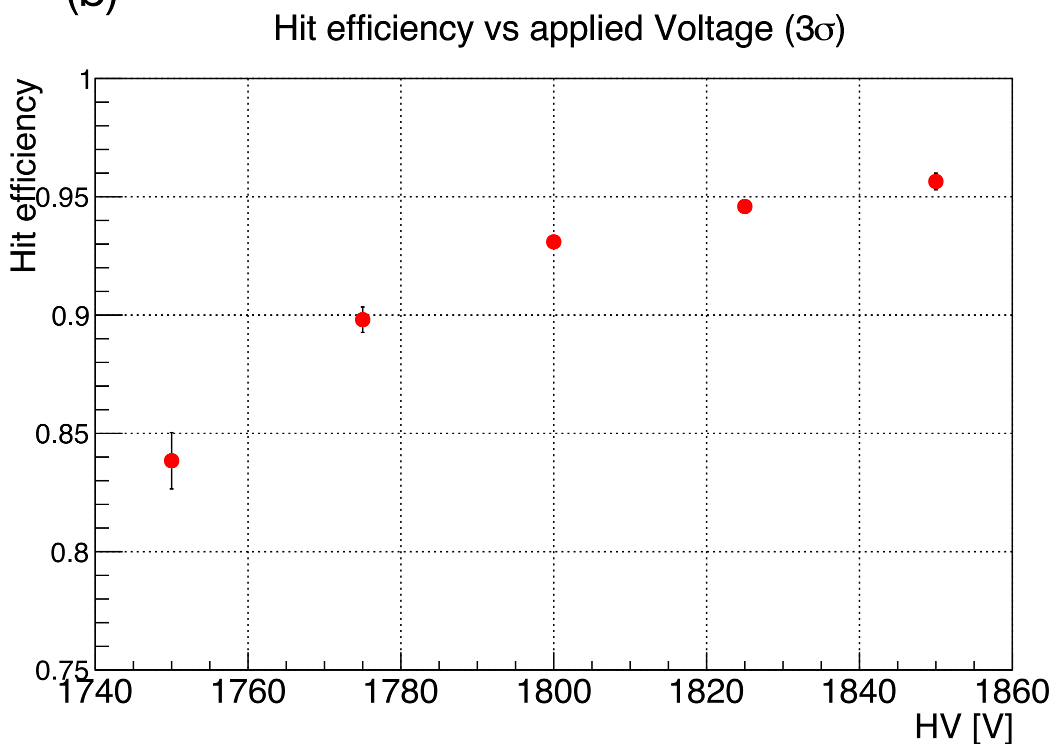

(b) Zoom view

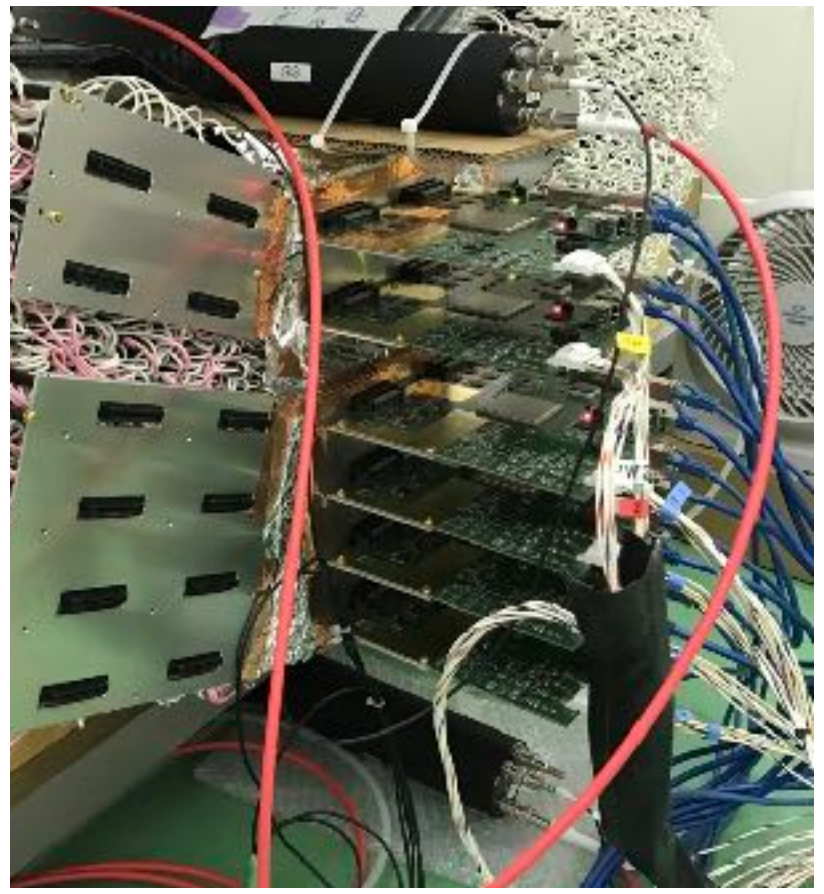



(a)




(b)



# Summary

- The COMET experiment aims to search for the $\mu$-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 momentum resolution for 105-MeV/c signal electrons.
- Construction of CDC was successfully completed.
- Performance tests are ongoing and reasonable resolution & efficiency are obtained so far.

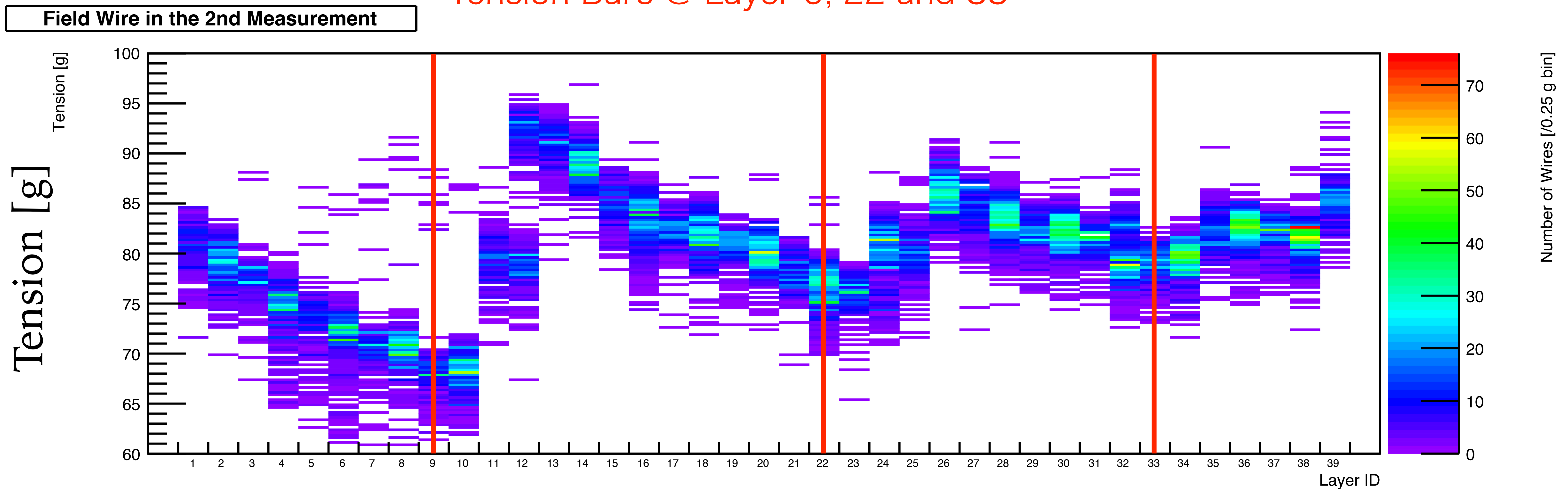
# Prospects

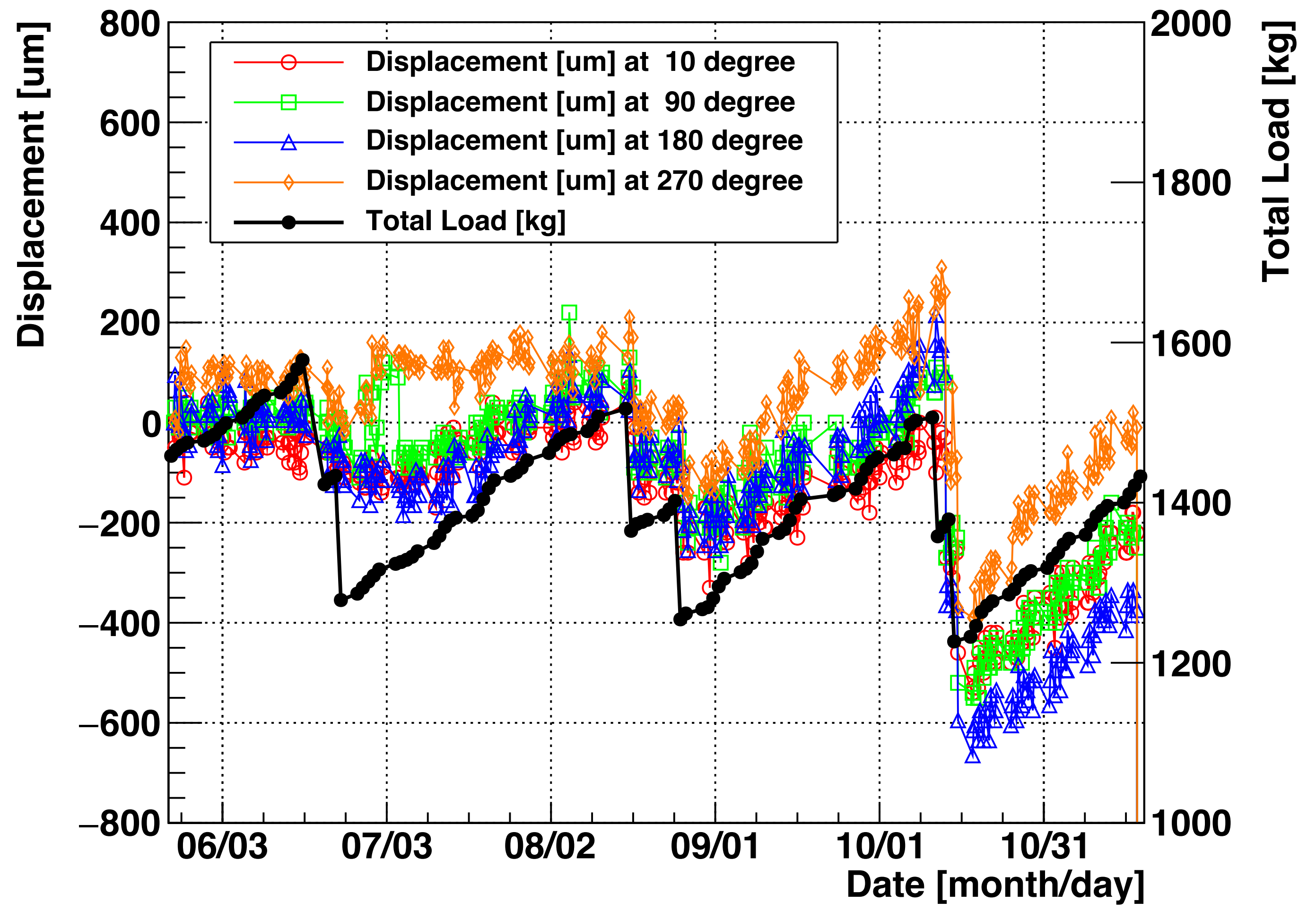
- Performance tests will be finished in this fiscal year.
- We plan to transport CDC from KEK to J-PARC and install to Detector Solenoid in 2019.
- Integrated cosmic-ray BG measurement will start from 2020.

# Backup

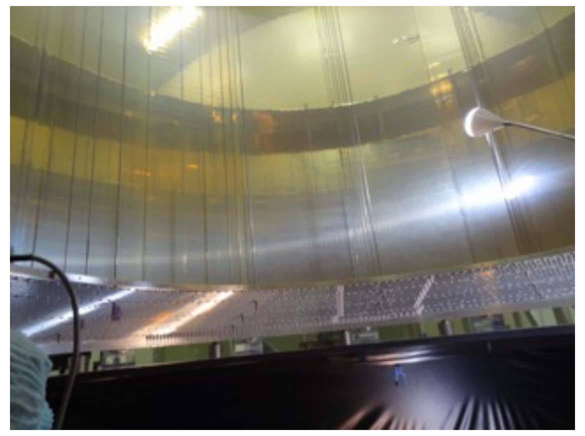
# Release of pre-tension @ wire stringing

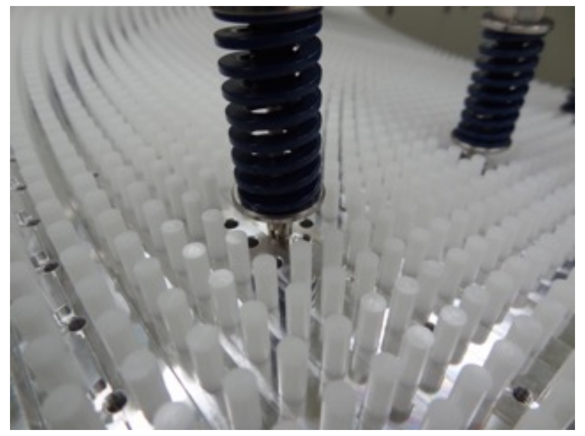
Tension Bars @ Layer 9, 22 and 33

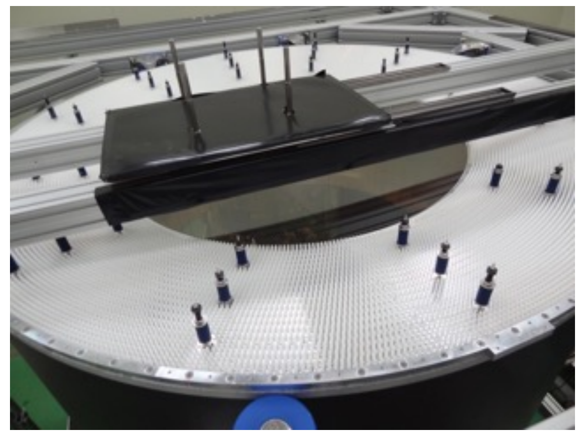



- Installation of the “Tension Bar” to apply the load (~ 1.4 ton) which corresponds to the load by 20,000 wires in the end





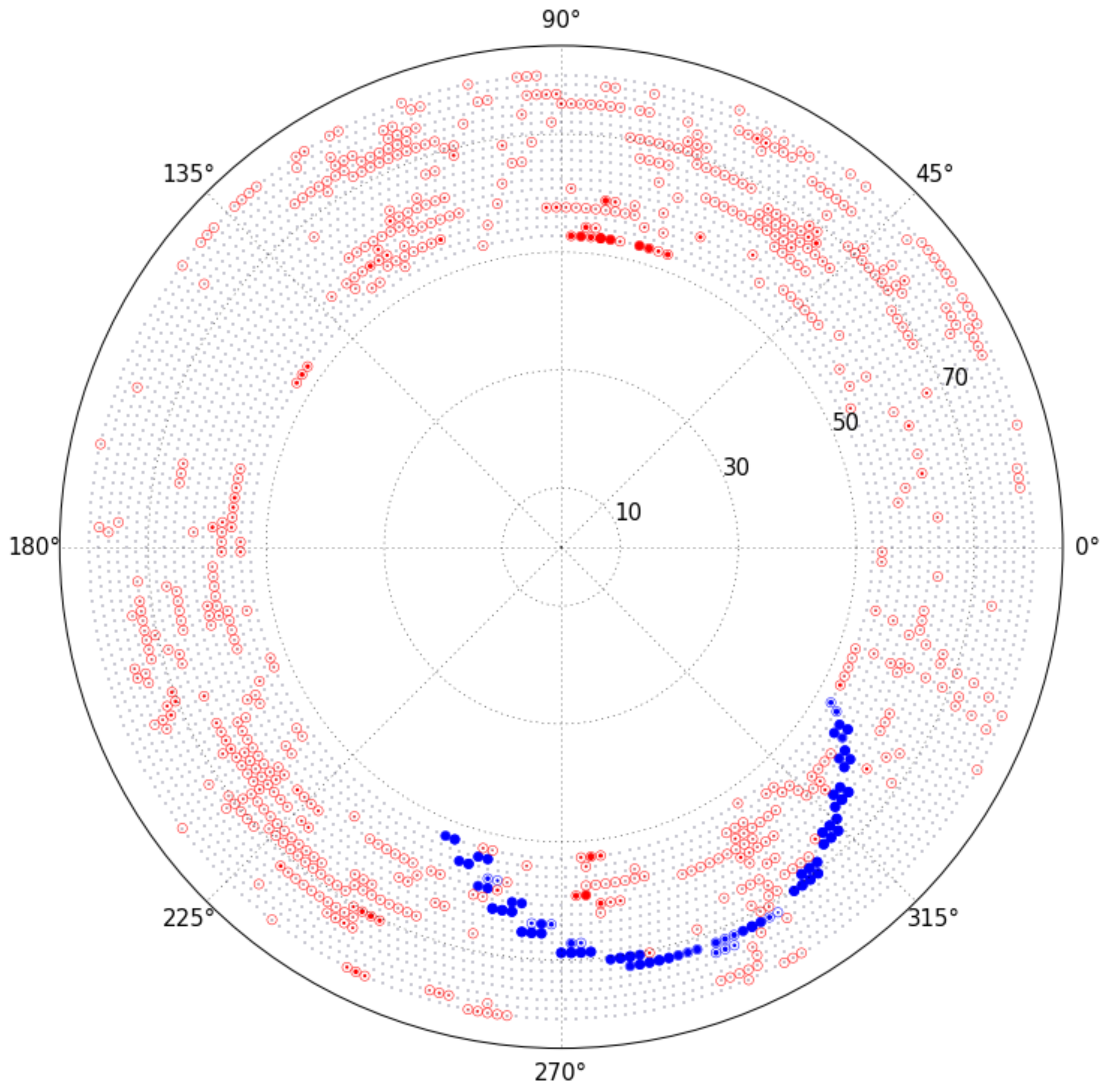


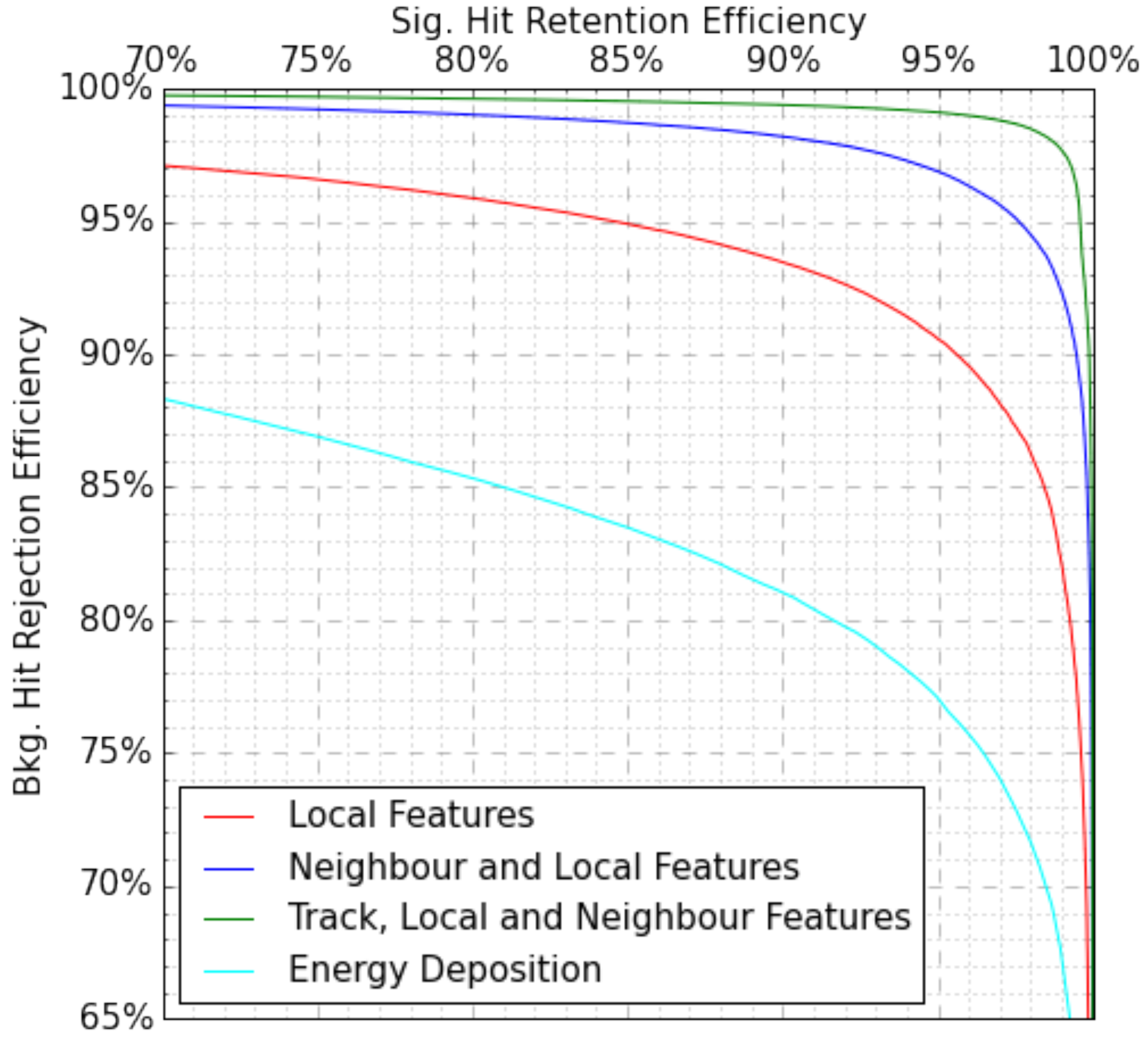
- 36 (12 x 3 layers) tension bars installed
- the tension applied with spring (3.07 kgf/mm)
- ~39 kg/tension bar -> 1.4 ton in total
- 9 feedthrough holes occupied by 1 bar
- following the progress of the wire stringing, the tension decreased and/or bar removed

- Installation of the “Dial Gauge and Reference Bars” to monitor the displacement between 2 endplates


- dial-gauges are located at 10°, 90°, 180°, 270°
- reference bar is double-layered structure not to harm wires with the removal
- checked the displacement by tension bar (it was consistent with the calculation)
- monitoring the dial-gauges 3 times / day

# High-level track trigger




(b) ROC curves with zoomed scale.

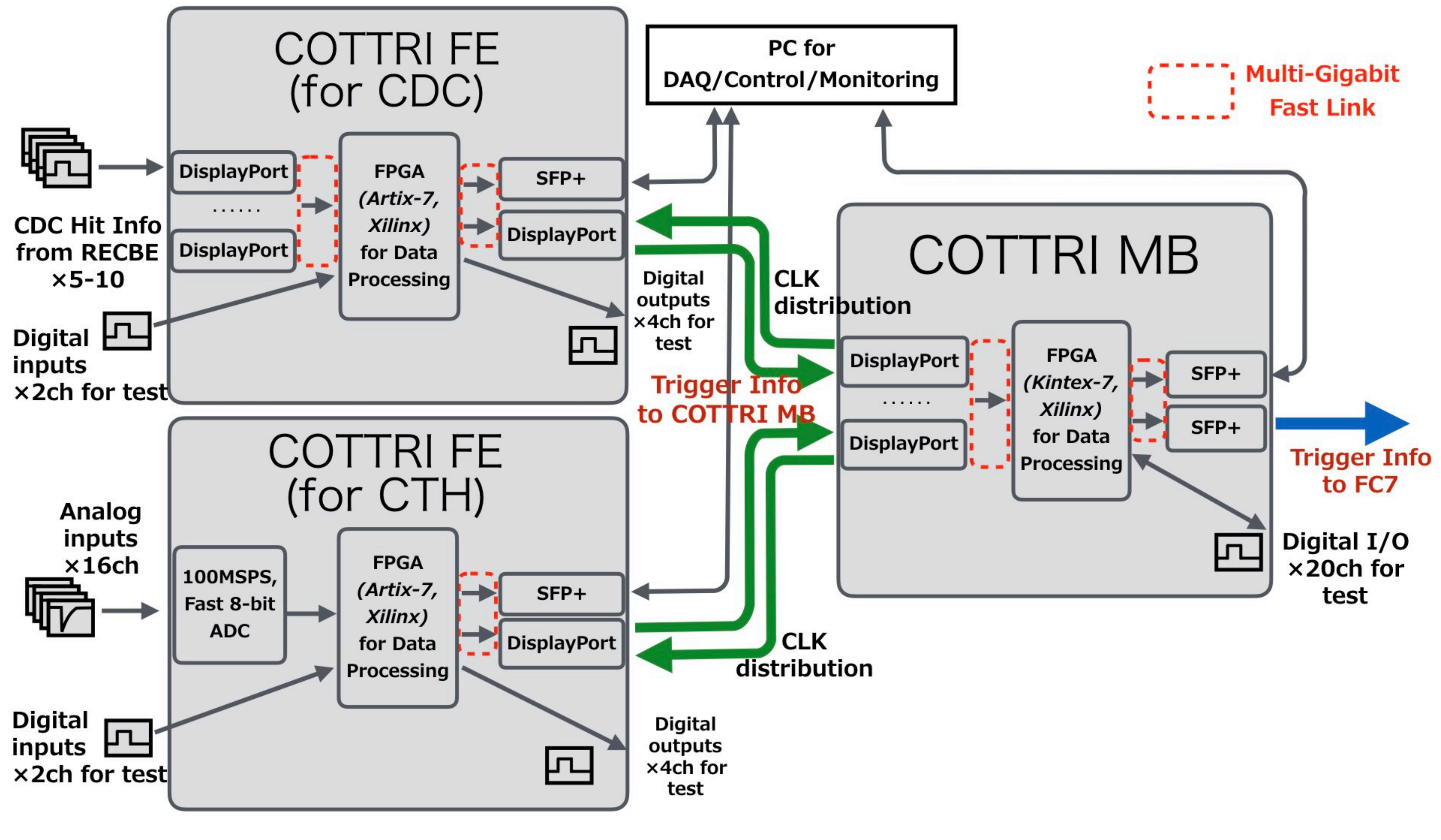
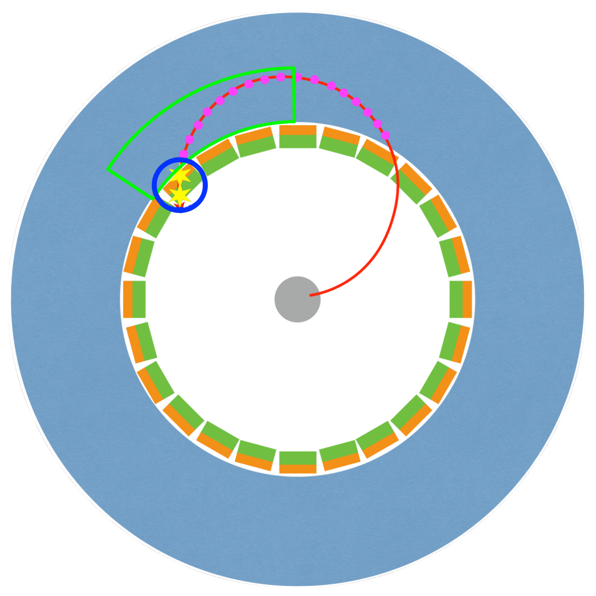


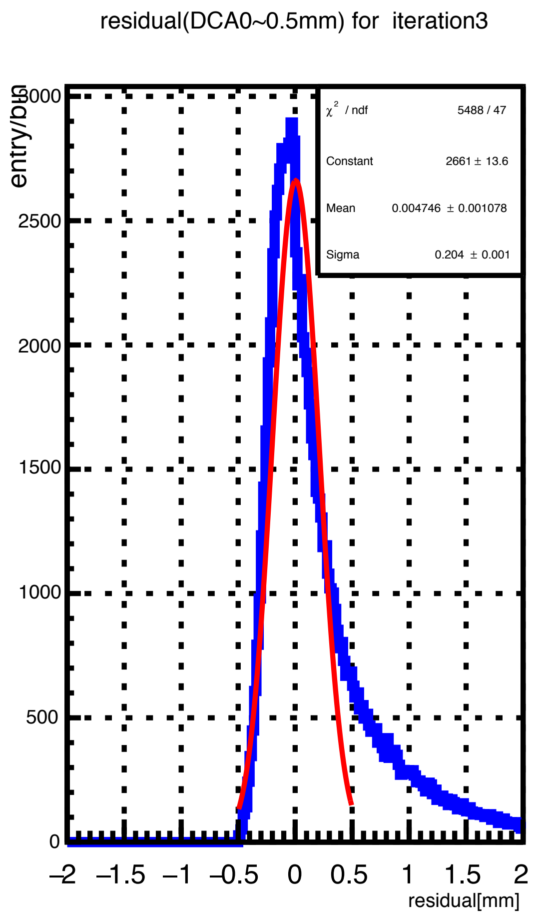

Figure 10.12: *Conceptual drawing of COTTRI system*

Software-level algorithm was already established.
We can reduce background hits into 1/20 while retaining 99% of signals.



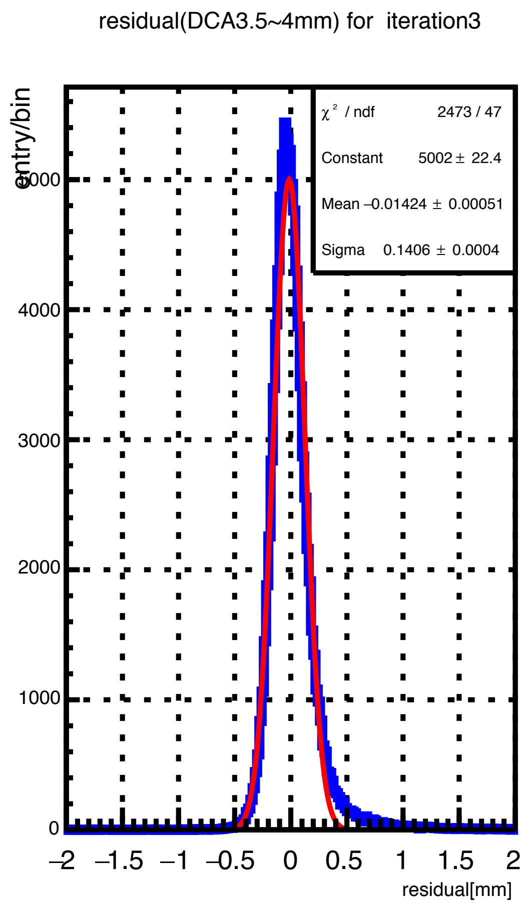
# Spatial resolution vs distance of closest approach

DCA = 0~0.5 mm



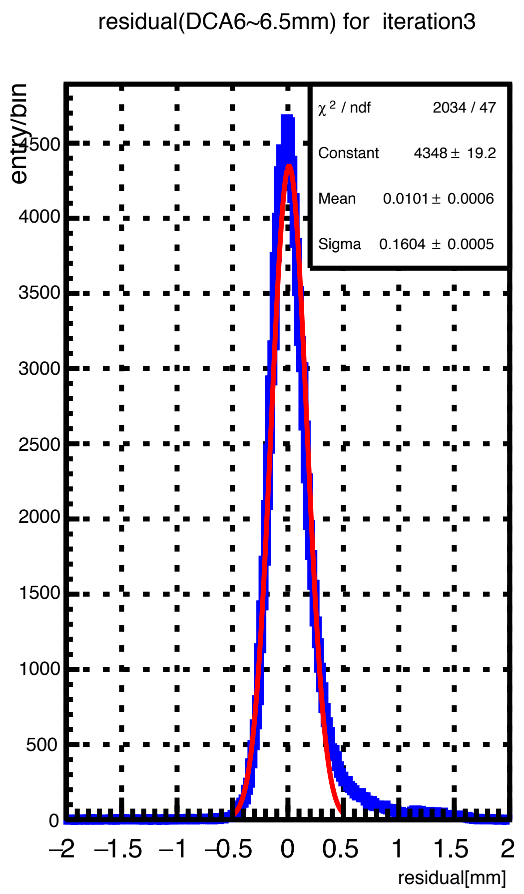

Residual [mm]

3.5~4.0 mm

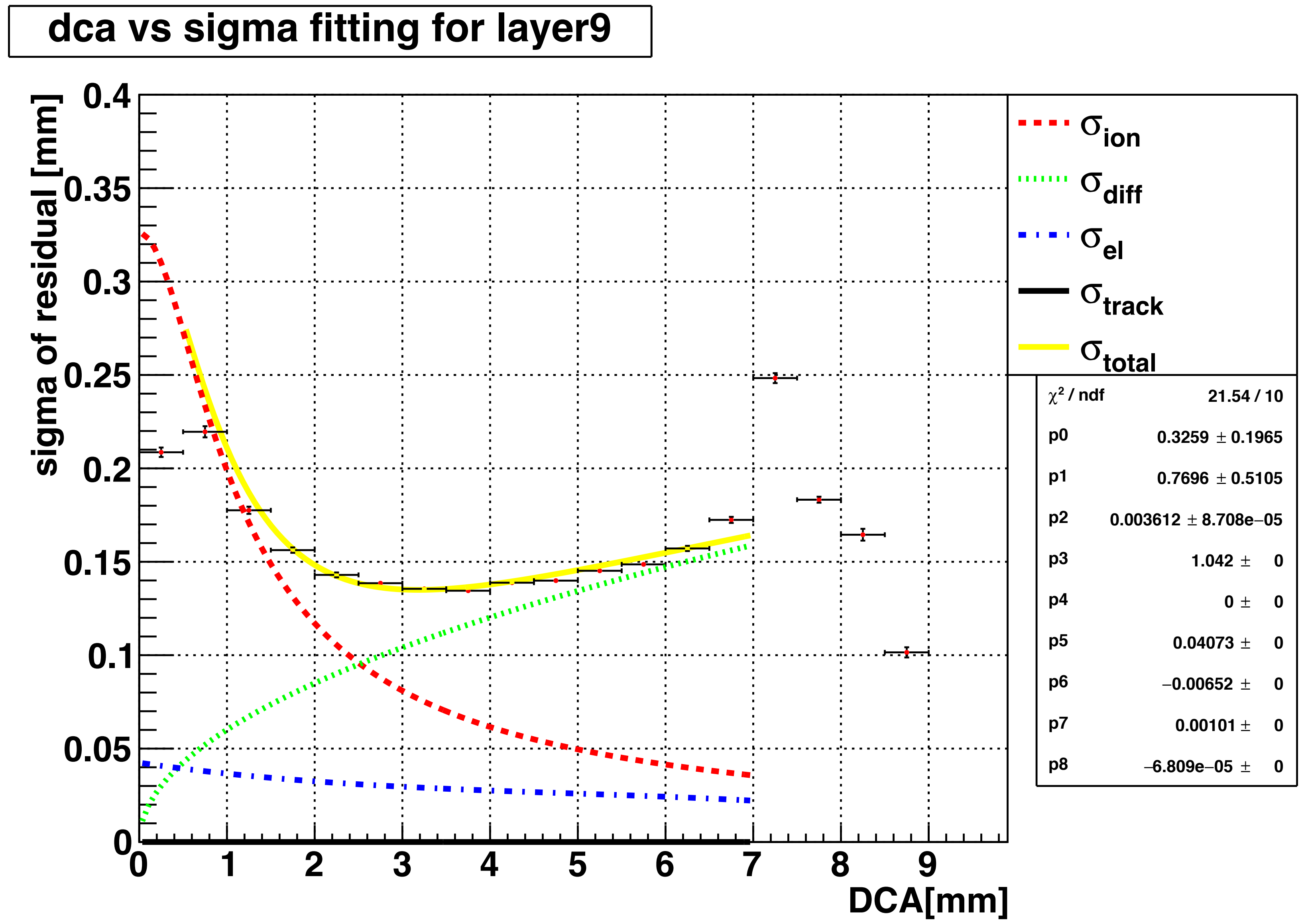


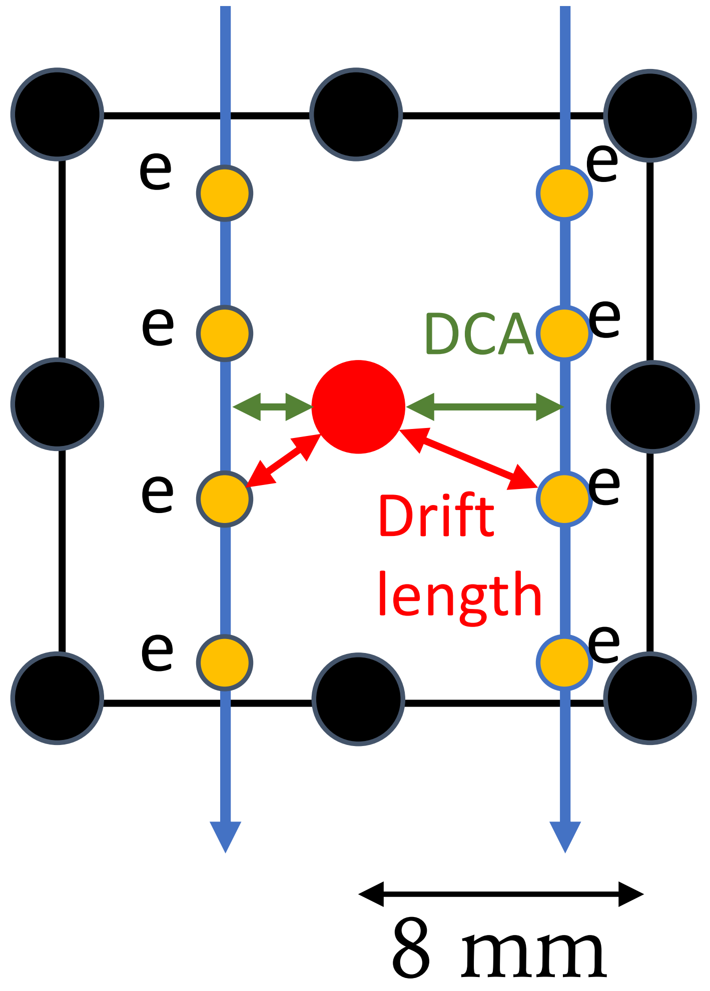

Residual [mm]

6.0~6.5 mm




Residual [mm]



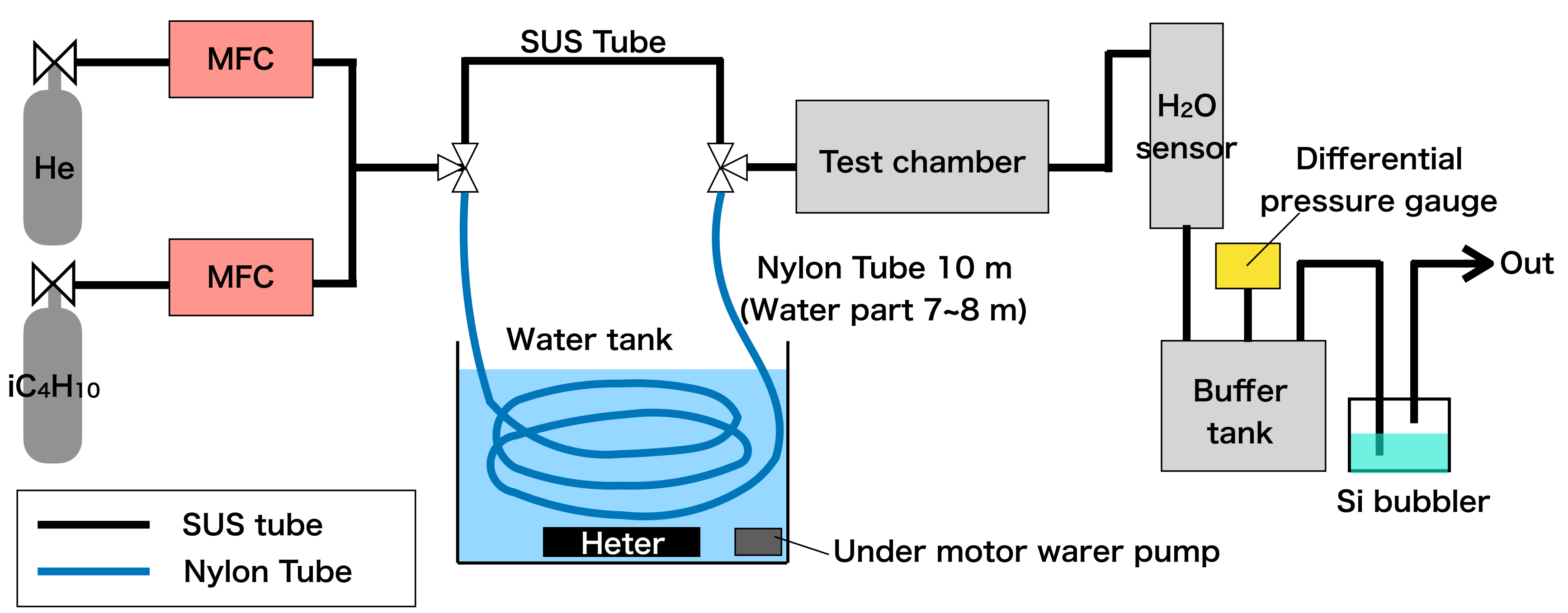



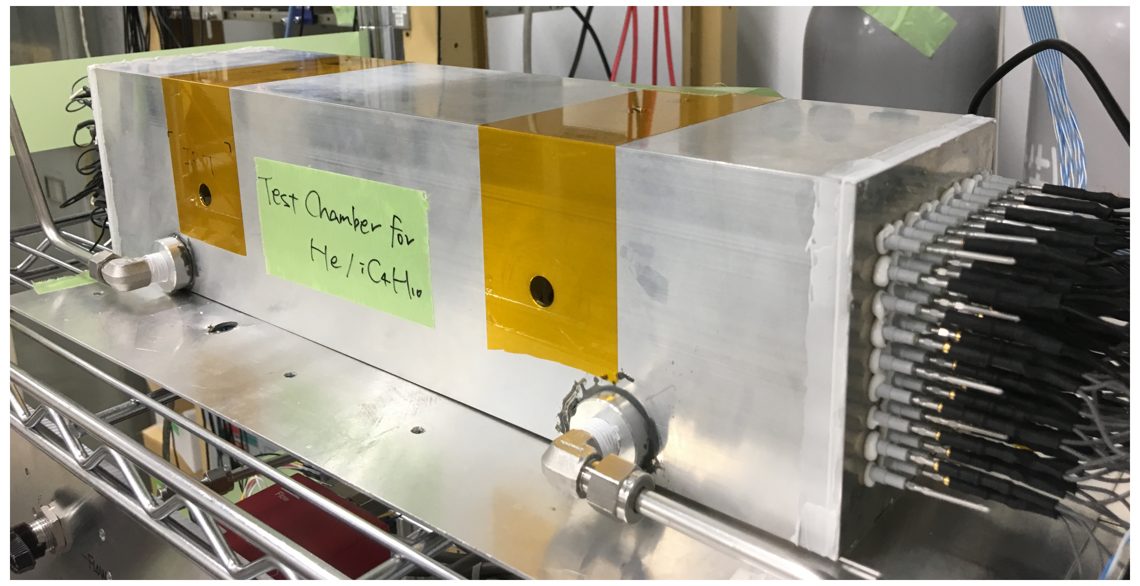

Near the sense wire

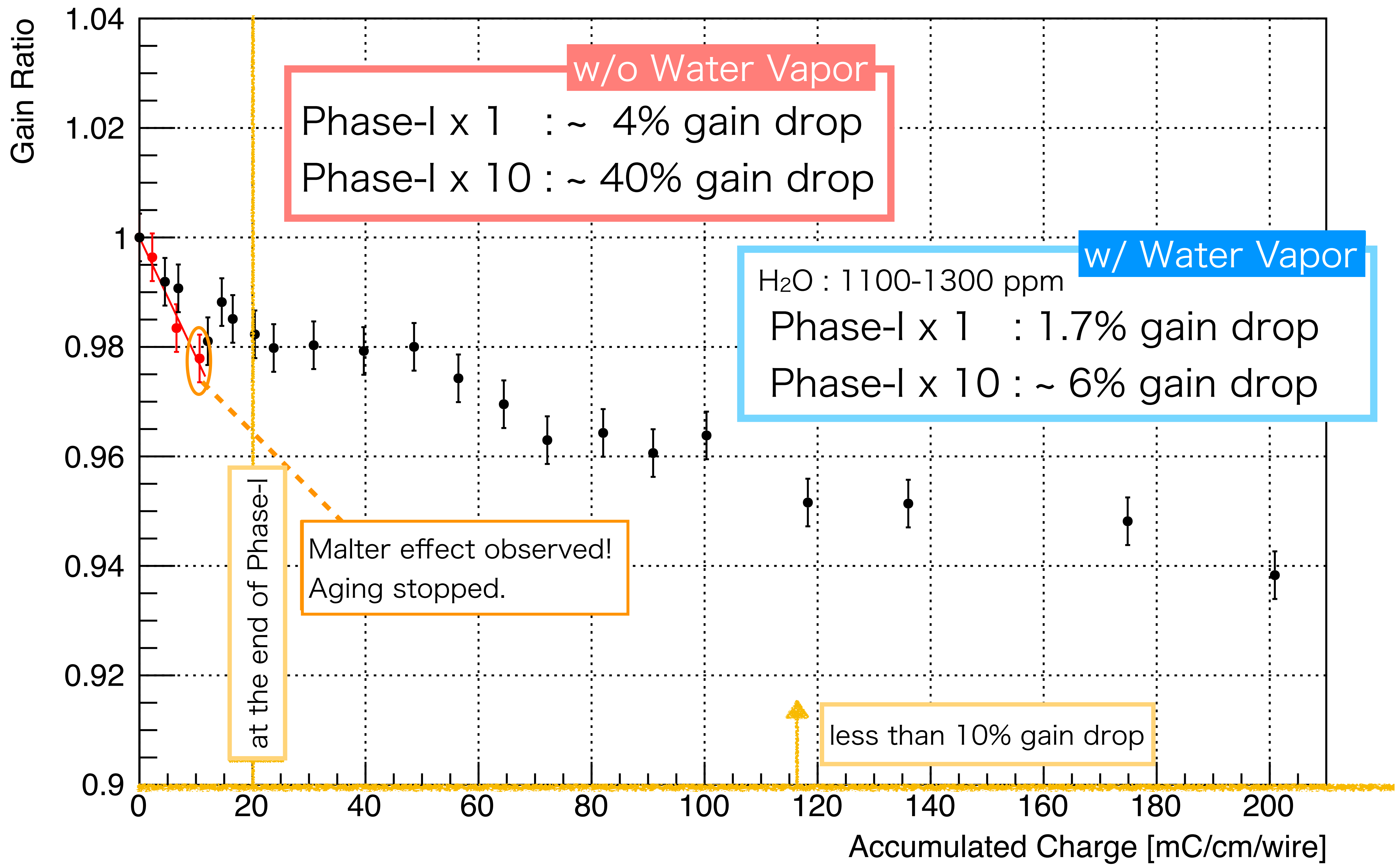
DCA < Drift Length

# 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

# Gas system

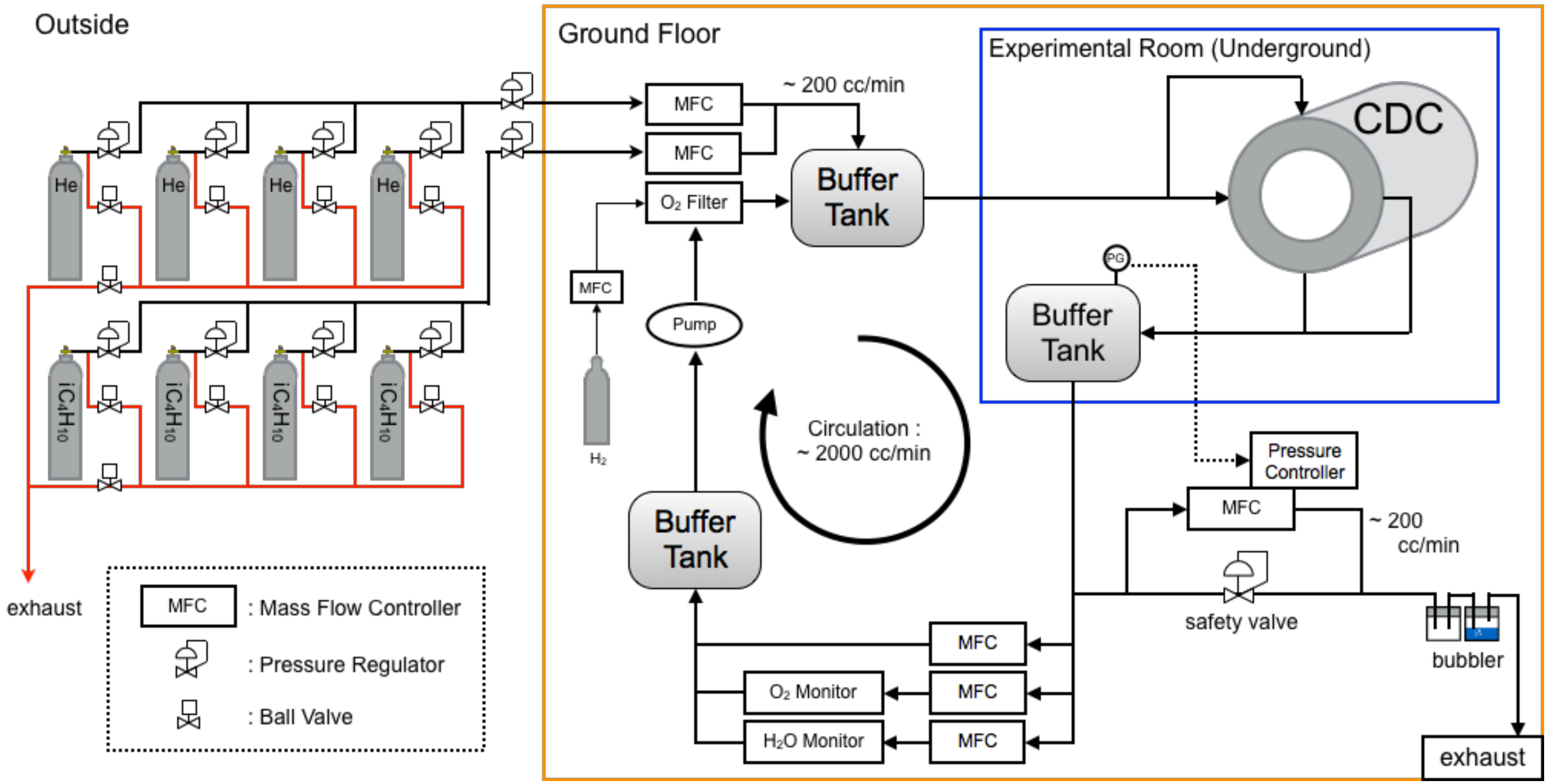



Figure 7.19: *Schematic view of the gas system for the CDC.*

# Electric field, drift velocity, etc

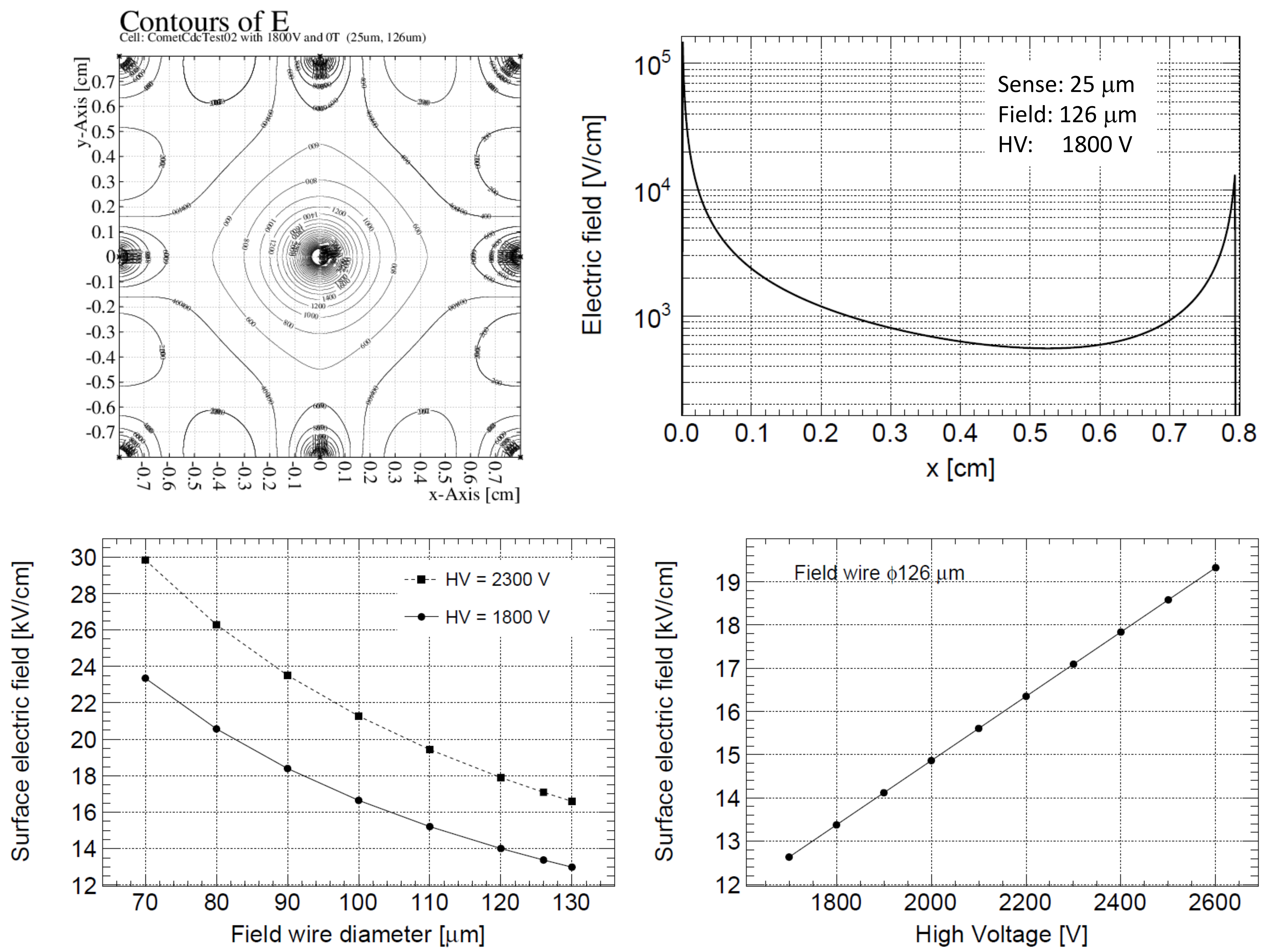
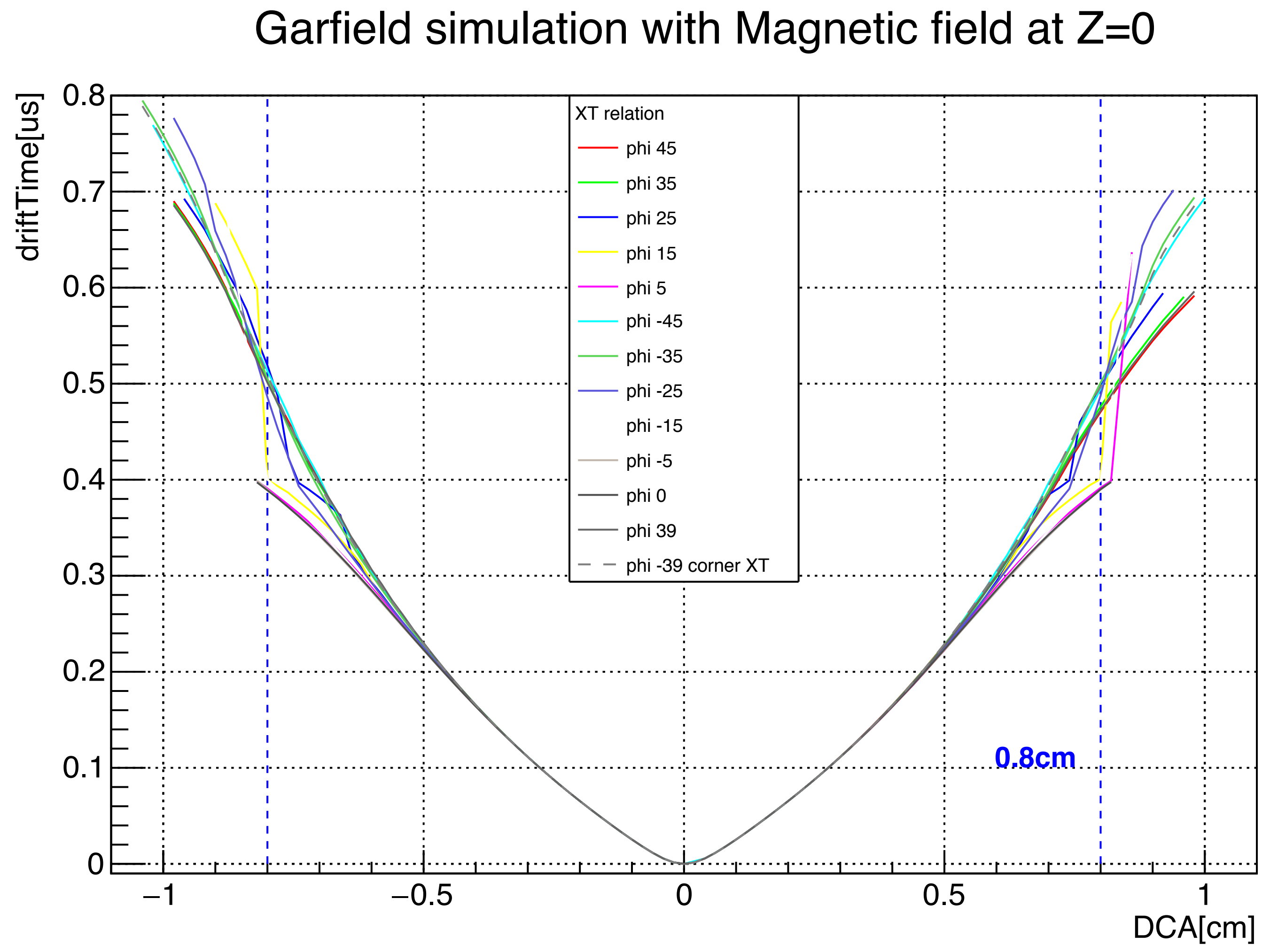


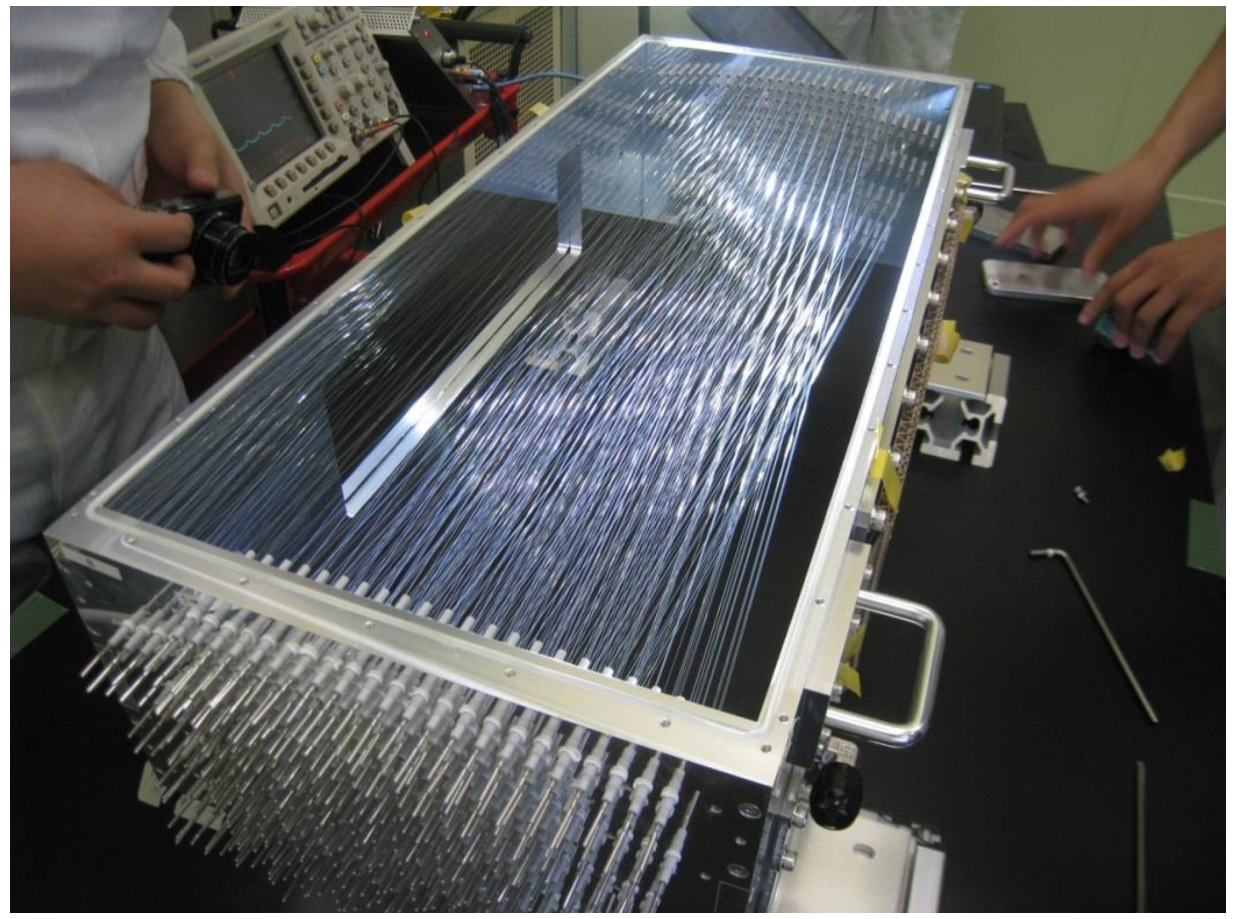

Figure 7.4: *Contours of electric field distribution calculated by* `Garfield` *for a cell of 1.6×1.6 cm$^2$, sense and field wires of $\phi$25 and $\phi$126 $\mu$m, and HV of 1800 V (top left), and the electric field distribution along the $x$-axis at $y = 0$ (top right). Electric field at surface of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

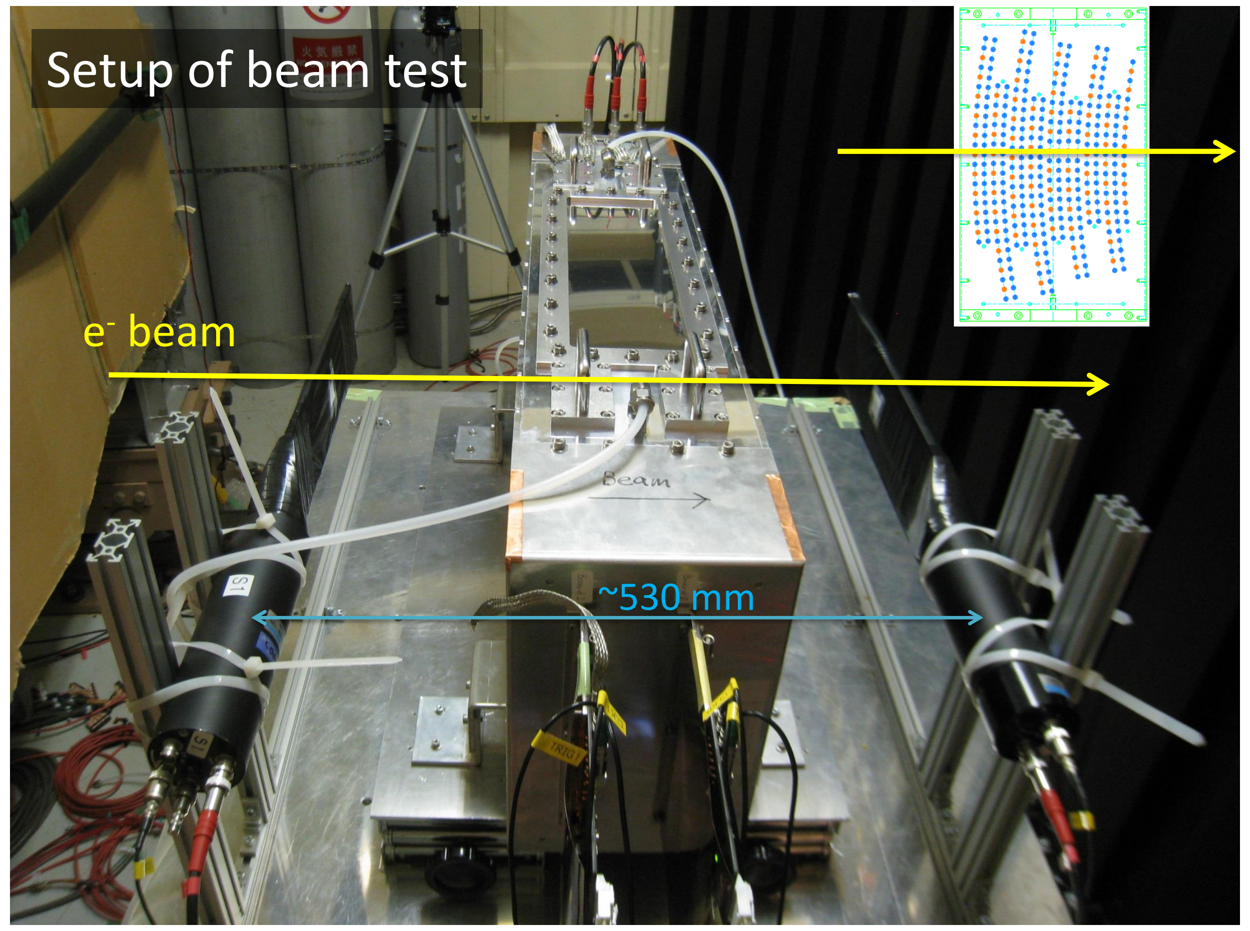



| Gas | $X_0$ (m) | $W$ (eV) | $\frac{dE^{MIP}}{dx}$ (keV/cm) | $n_T^{MIP}$ (cm$^{-1}$) | $n_p^{MIP}$ (cm$^{-1}$) |
|---|---|---|---|---|---|
| He:i-$C_4H_{10}$ (85:15) | 954 | 38 | 1.14 | 40 | 18 |
| He:i-$C_4H_{10}$ (90:10) | 1310 | 39 | 0.88 | 29 | 14 |
| He:i-$C_4H_{10}$ (95:5) | 2102 | 40 | 0.61 | 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 |

# 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) | |

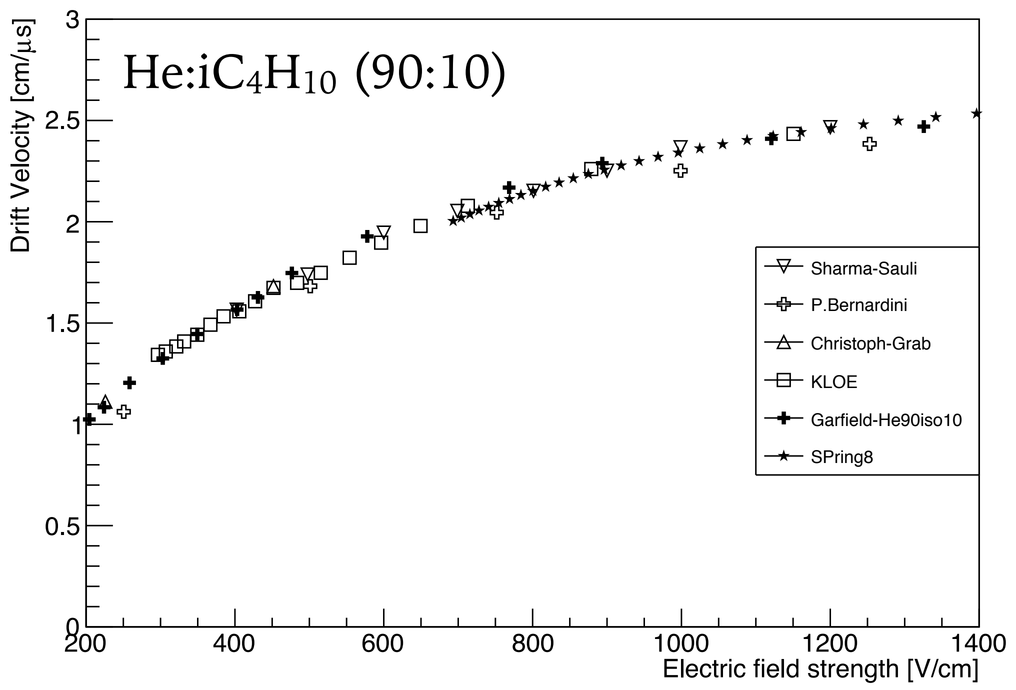



Figure 8: *The drift velocity versus the electric field for He−$iC_4H_{10}$(90/10)by comparing with Garfield++ simulation and experiment of Christoph-Grab[7], P.Bernardini[8], Sharma-Sauli[9] and KLOE[10]*

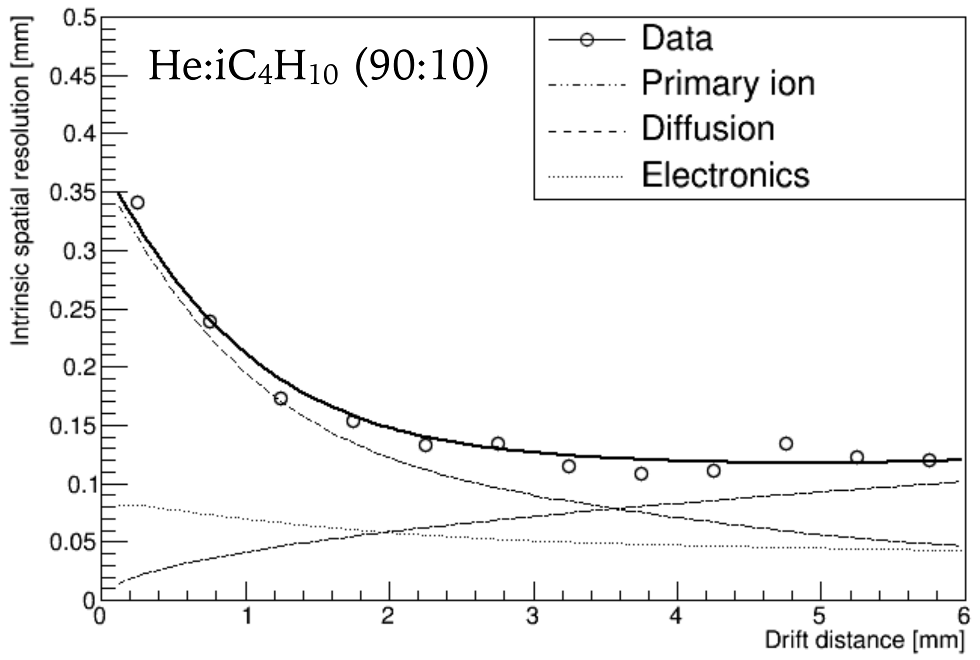



Figure 9: *Spatial resolution as a function of drift distance distance for He−$iC_4H_{10}$(90/10)at 1800 V. The line shows fitted curve.*

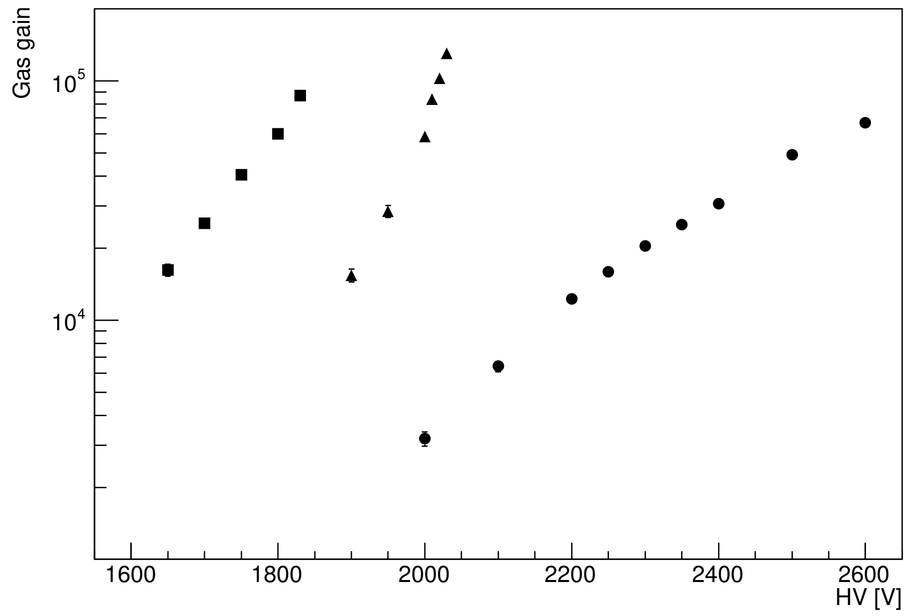



Figure 11: *Relation between gas gain and high voltage for three types of gas mixture. Squres stand for He−$iC_4H_{10}$(90/10). Full circles stand for He−$C_2H_6$(50/50). Triangles stand for He−$CH_4$(80/20).*

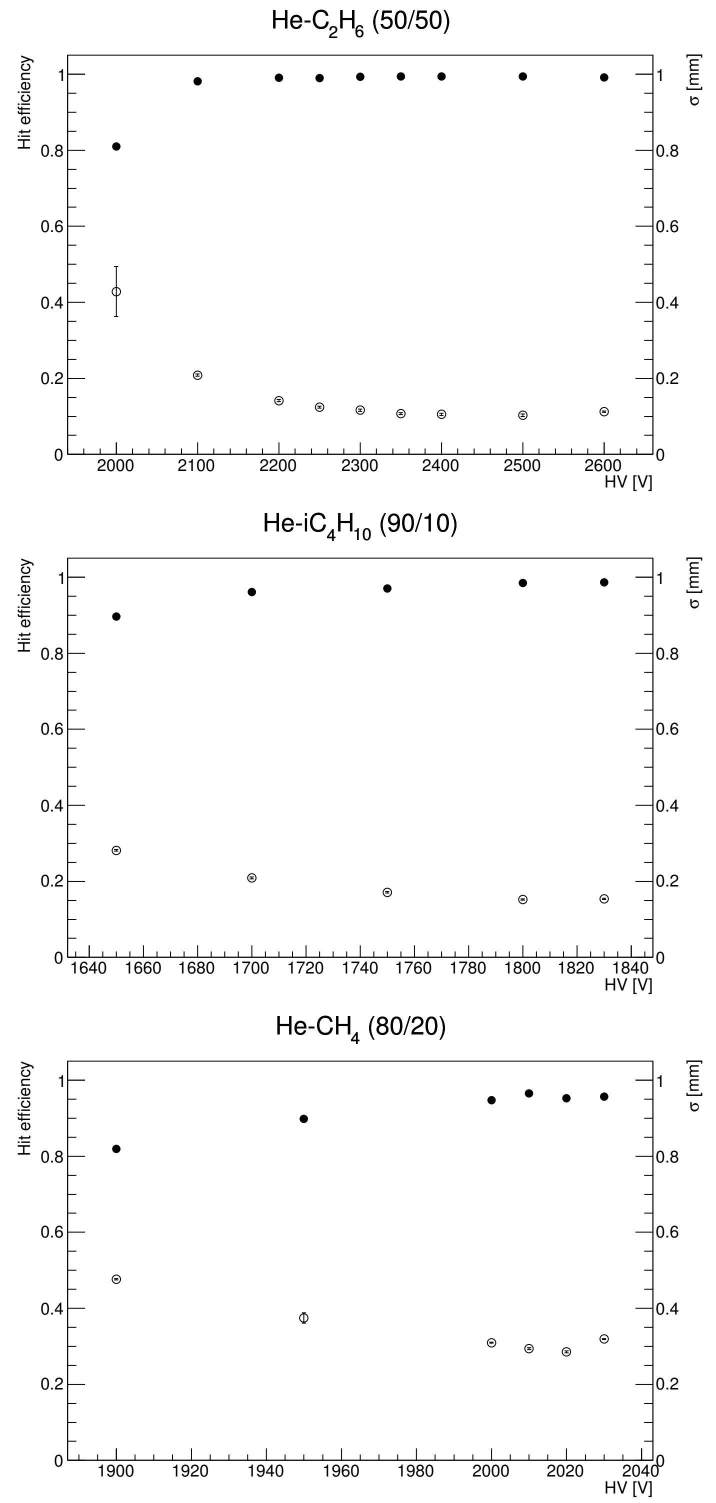
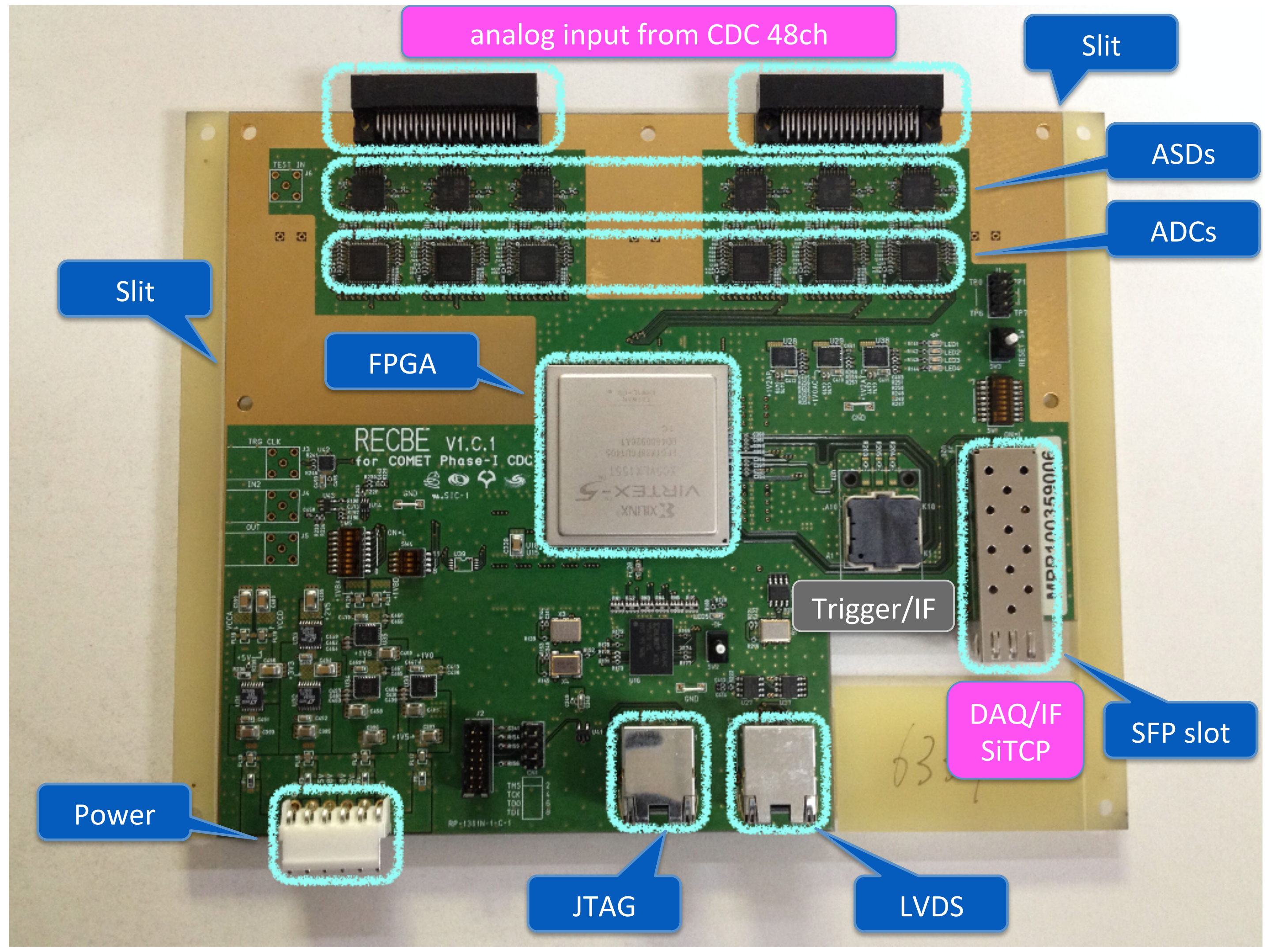


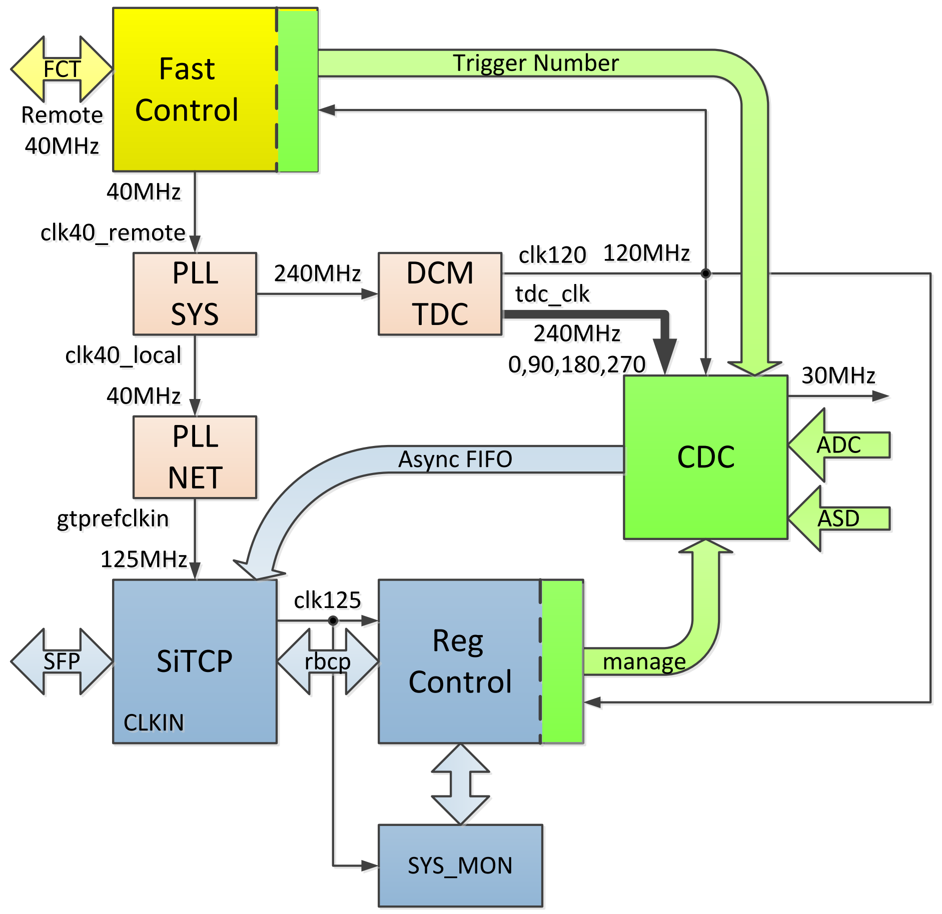

Figure 10: *Cell efficiency (full circles) and spatial resolution (open circles) as a function of the applied voltage for 3 different types of gas*

# Frontend readout electronics




Frontend readout board: **RECBE**
(= Readout Electronics for CDC for Belle-2 Experiment)

TDC: 960 MHz
ADC: 30 MHz sampling



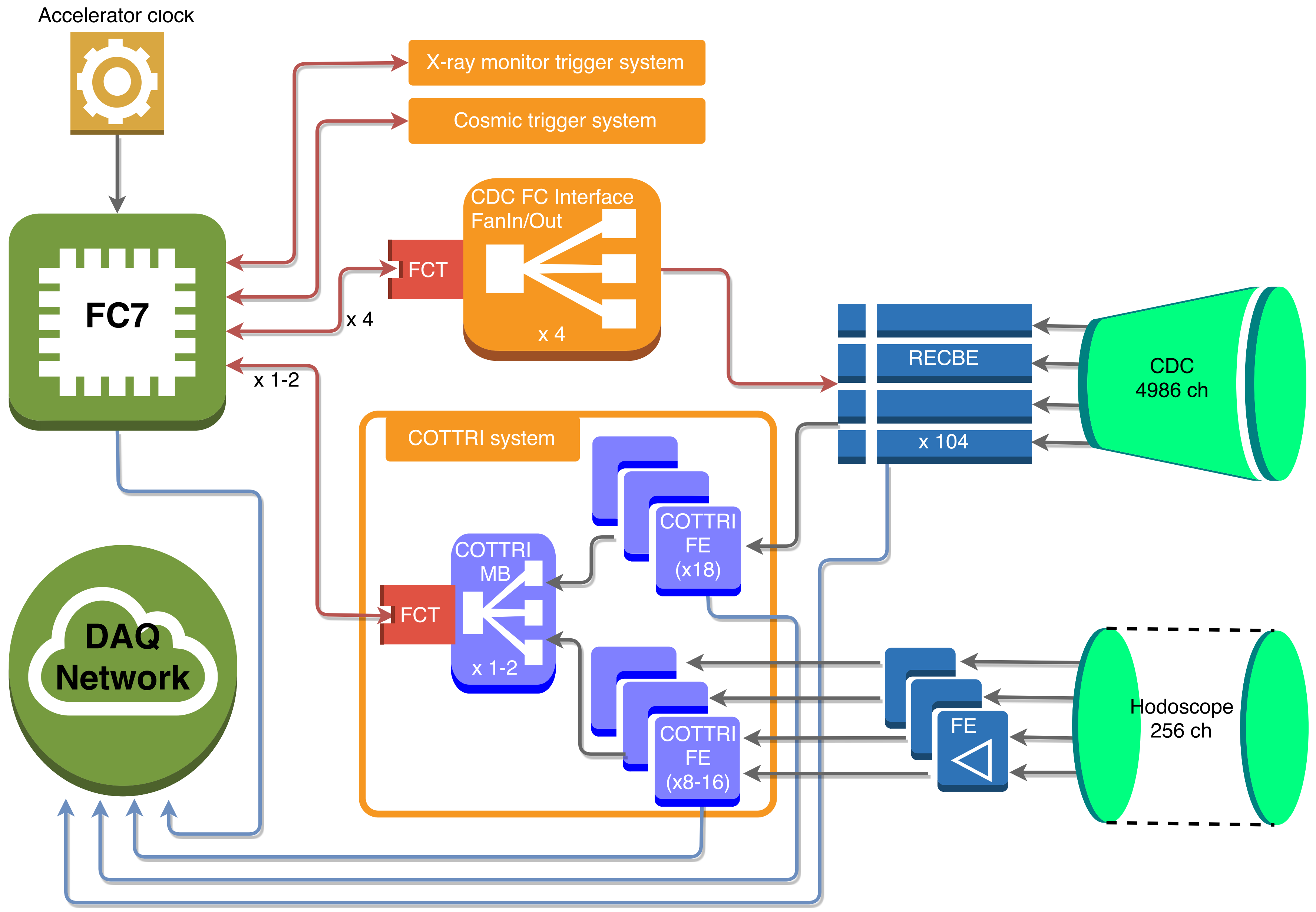

Firmware design

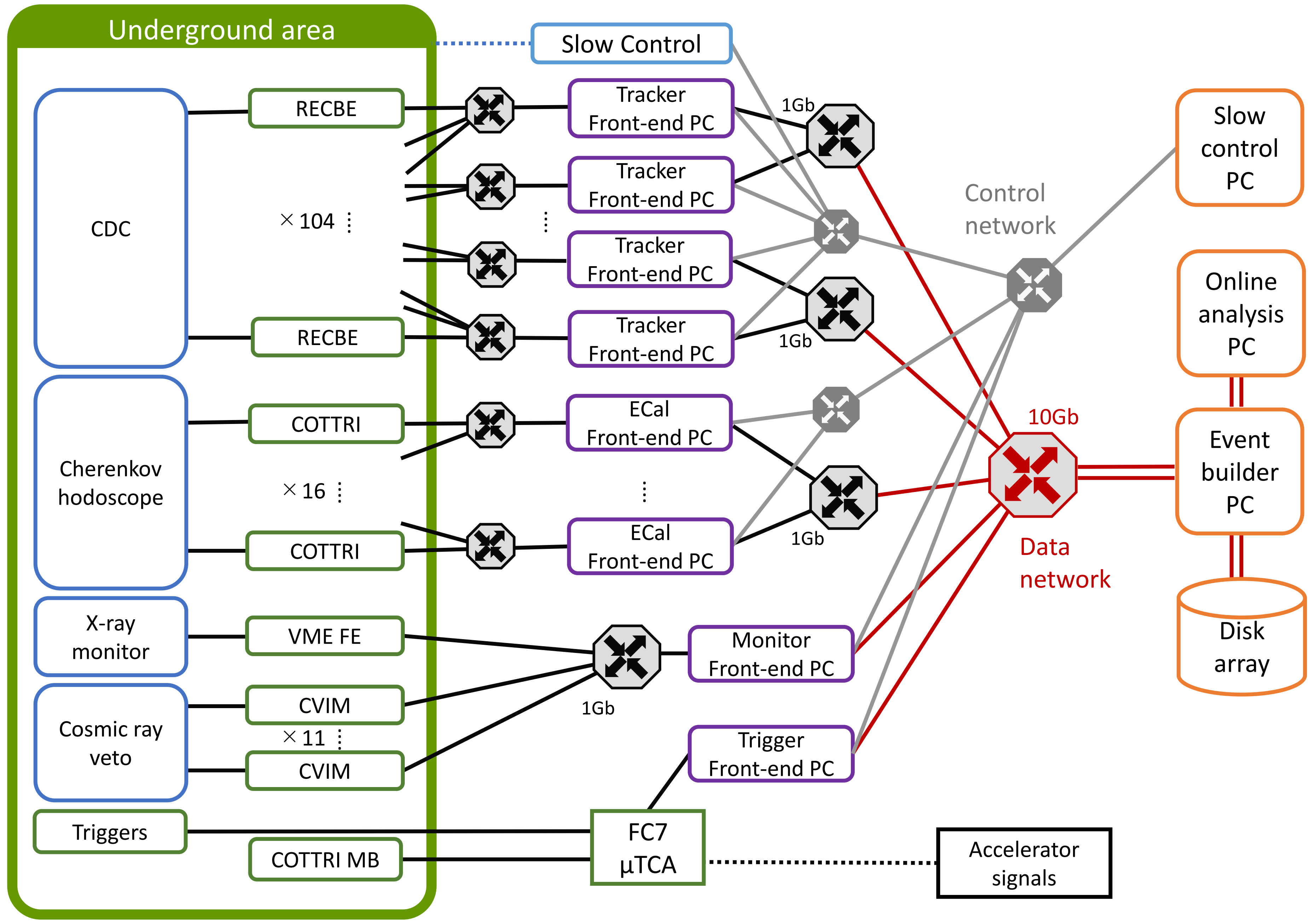
All 128 RECBEs were already fabricated and QA was done by IHEP group.

- 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.

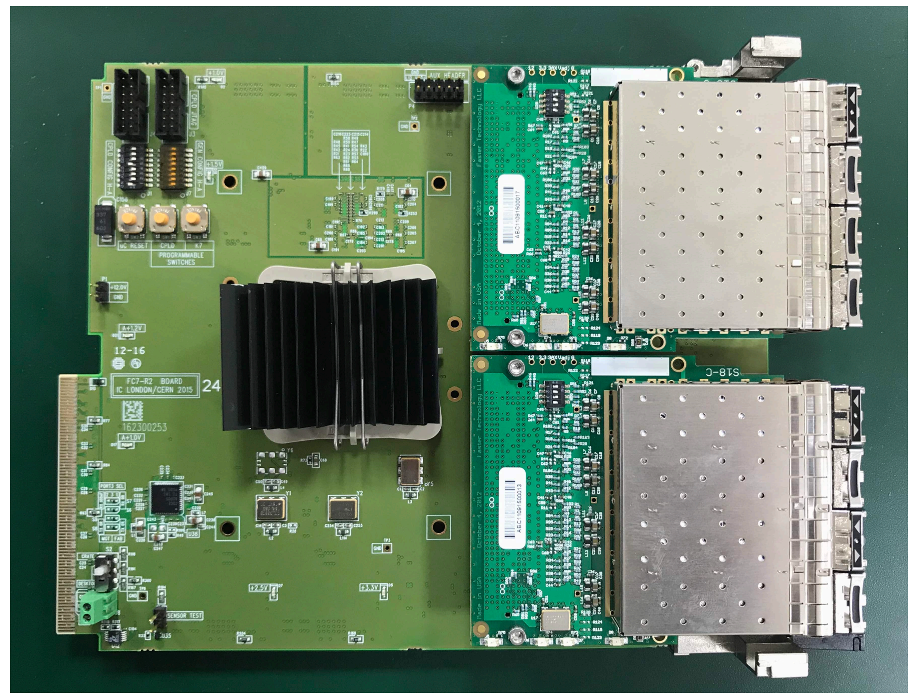
*# Predicted dose is 0.1~0.2 kGy for Phase-1*

# Trigger & DAQ system

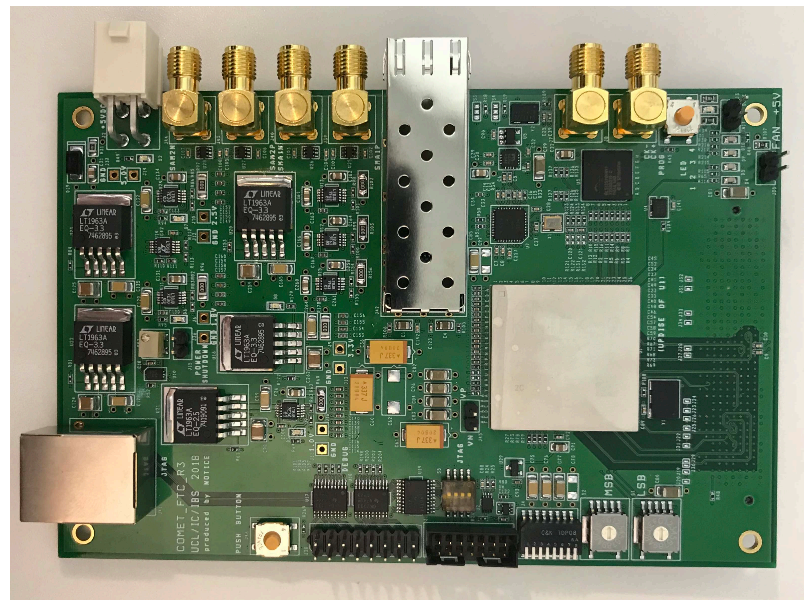



FC7



FCT

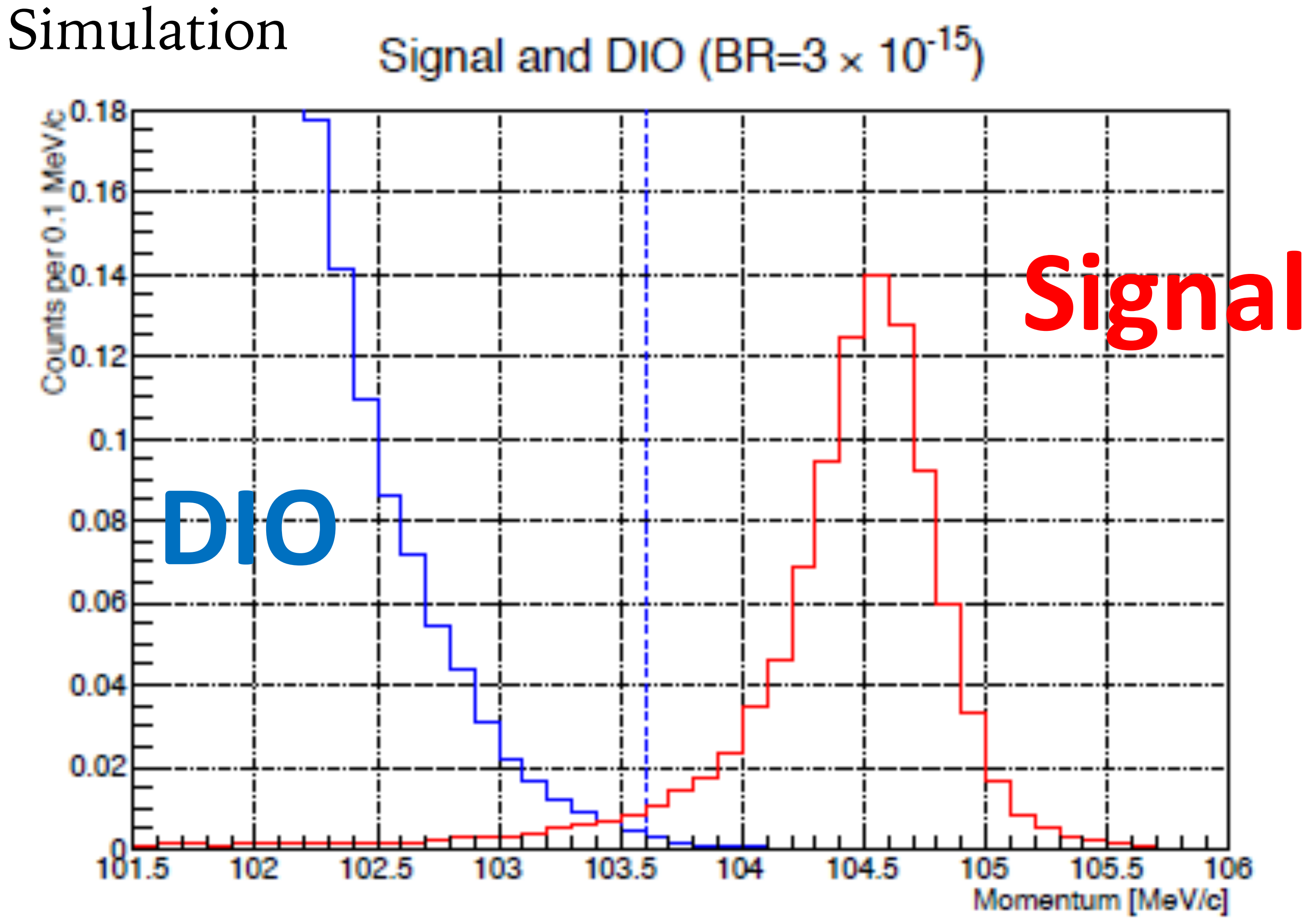


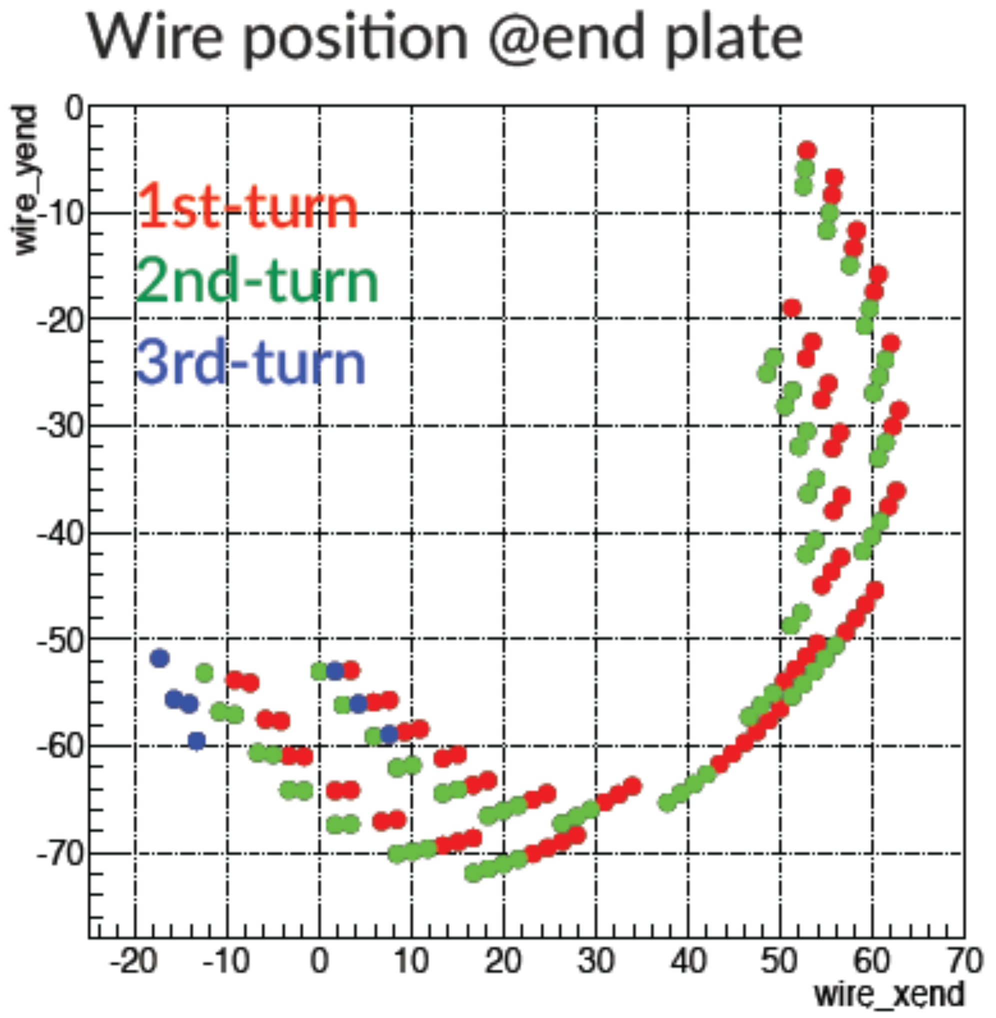
I/F board for FCT & RECBE

# Tracking

- Pilot studies written in TDR have shown a good potential of CDC tracking which is sufficient for Phase-I sensitivity.
  - 200 keV/c resolution with very little tail & 18% acceptance.
- Multi-turn hits make things challenging…
  - Momentum tail come form multi-turn events.
  - Hits from other turns are too close to a track, providing a many local minima.
- Taking into account the multi-turn issue, full tracking packages from track finding to fitting are under development.
  - Traditional ways (circle & helix fitting), modern ways (deep learning, neural network), or other way around (topological method).

Simulation



# Sensitivity & Background

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

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

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

| 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 | $\leq 0.0038$ |
| | Radiative pion capture | 0.0028 |
| | Neutrons | $\sim 10^{-9}$ |
| Delayed Beam | Beam electrons | $\sim 0$ |
| | Muon decay in flight | $\sim 0$ |
| | Pion decay in flight | $\sim 0$ |
| | Radiative pion capture | $\sim 0$ |
| | Anti-proton induced backgrounds | 0.0012 |
| Others | Cosmic rays† | $< 0.01$ |
| Total | | 0.032 |

† This estimate is currently limited by computing resources.