# Fast Online Trigger using FPGA-based Event Classification for the COMET Phase-I

## Outline

- Introduction
  - COMET Phase-I
  - Trigger requirement
- Event classification
- Development status of Trigger System
  - Trigger logic
  - New trigger board
  - Performance in a cosmic-ray test.


Year-End Presentation 2019

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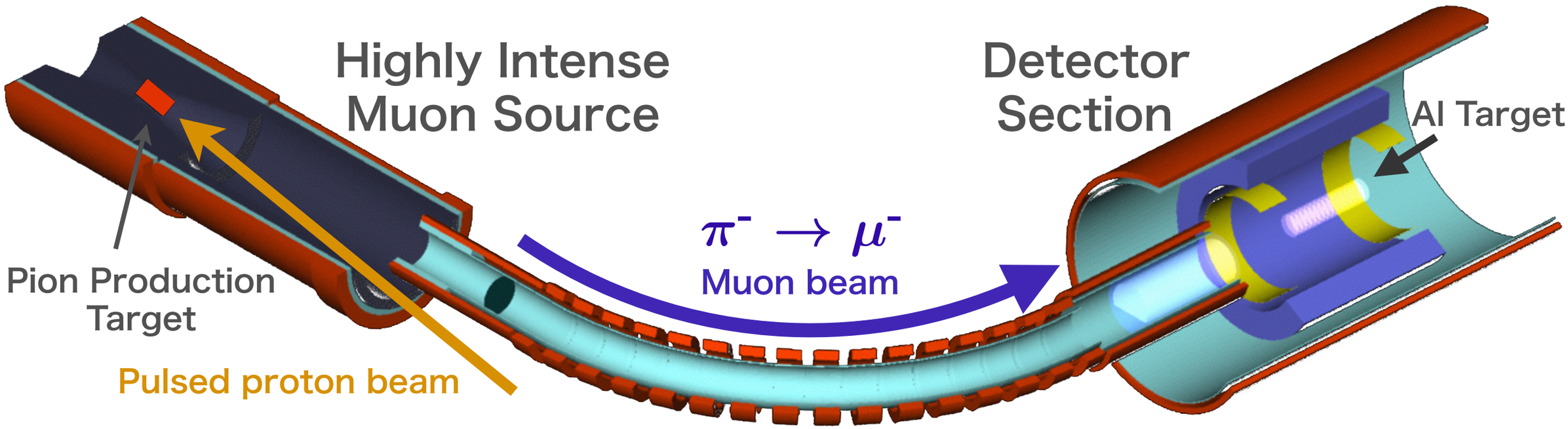
# COMET Phase-I @J-PARC, Japan




**Purpose : Search for neutrino-less μ-e conversion in Al**

- Single Event Sensitivity: ~ $3 \times 10^{-15}$

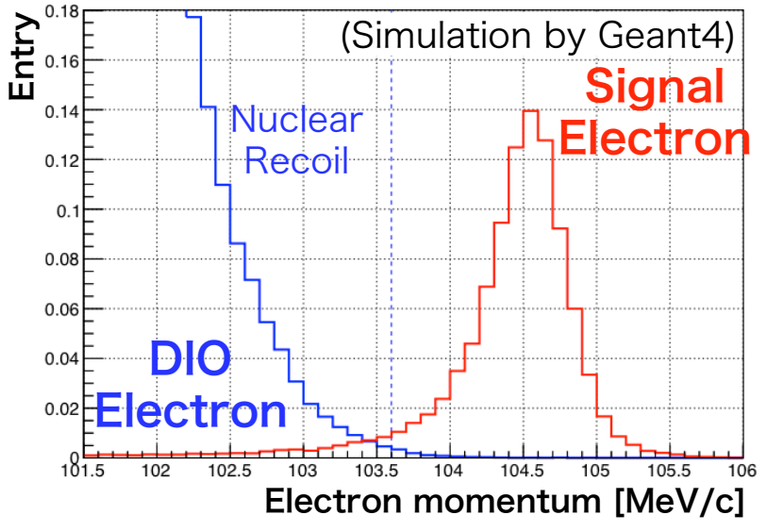
**Detector :** Cylindrical Detector System (CyDet)

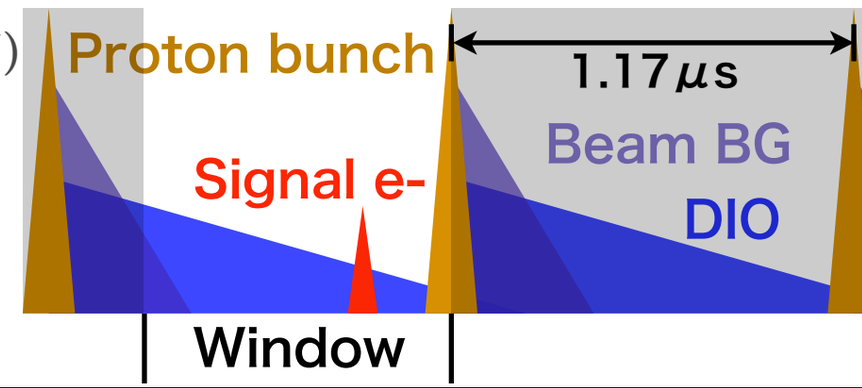
**Signal :** 105-MeV single electron

**Background (BG)**

- Decay-In-Orbit electron : $\mu^- + N_{\mathrm{Al}}(A,Z) \rightarrow e^- + \nu_\mu + \overline{\nu}_e + N_{\mathrm{Al}}(A,Z)$
  - Momentum resolution for the 105-MeV/c electron : < 200 keV/c
- Beam related background
  - Proton beam pulsing high proton extinction

Momentum Distribution (S.E.S : $3 \times 10^{-15}$)

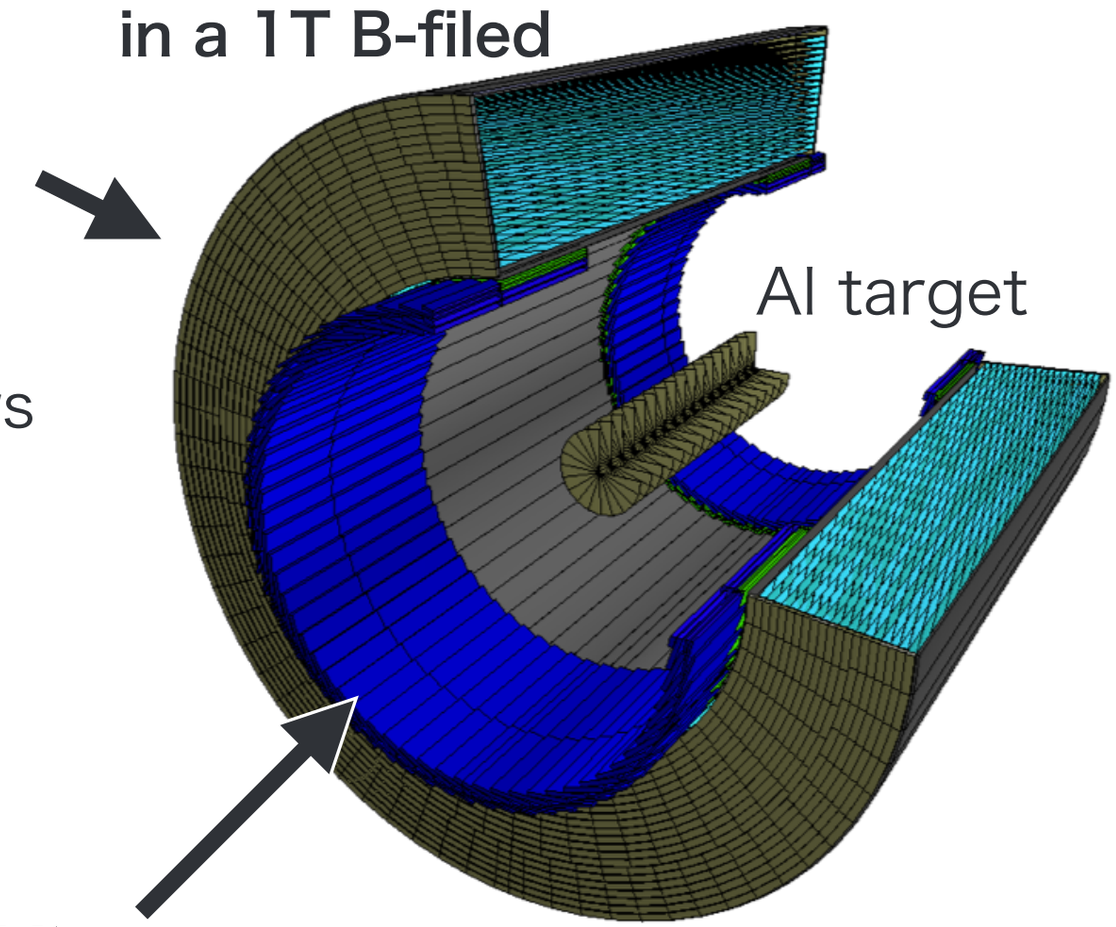


# Cylindrical Detector System

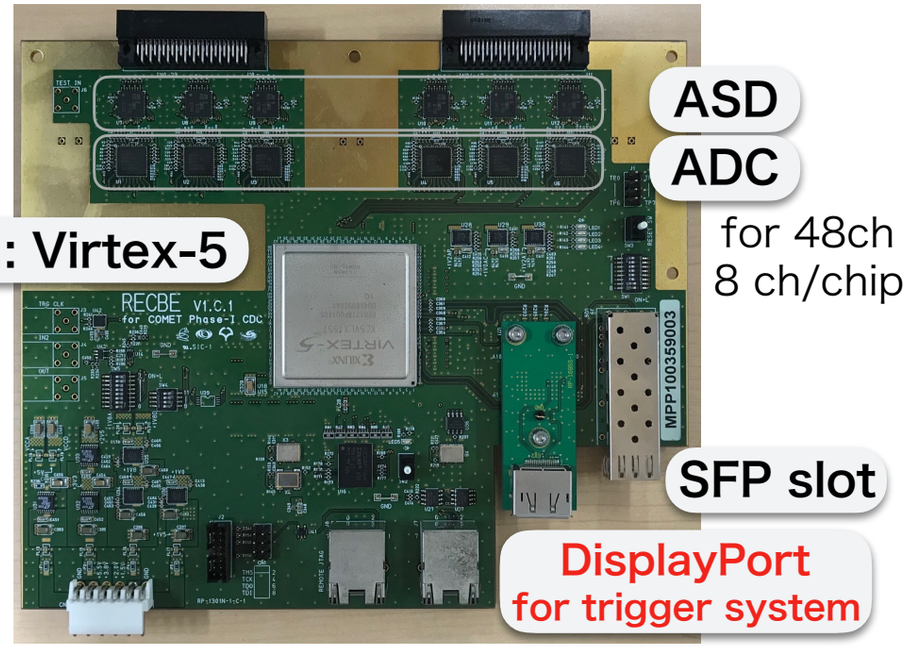
## Cylindrical Drift Chamber (CDC)

- Measure the electron momentum
- ~5000 sense wires, 18 of all stereo layers
- Readout electronics: RECBE
  - Developed by the Belle II CDC group
  - Waveform and timing information

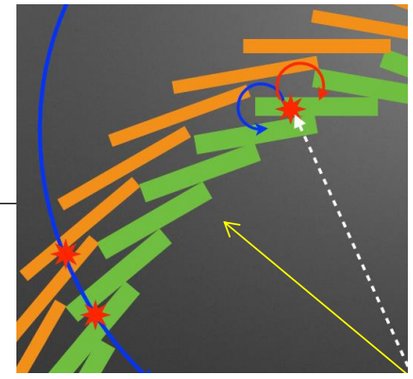



## Cylindrical Trigger Hodoscope (CTH)

- Measure time of flight of the electrons in CDC
- 48 sets of Cherenkov and Scintillation counters, located on both upstream and downstream sides
- 4-fold hits coincidence



# Trigger requirement



4-fold coincidence

**Trigger rate : <<24 kHz**

To be as small as possible to ensure almost 100% DAQ efficiency

Main constraint : Use of **1** backend PC (~1 GiB/s)

4-fold coincidence of CTH : ~27 kHz

**CDC Hit information : ??**

→ **COTTRI System**
**(COmeT TRIgger)**

**Latency : <5 μs**

Buffering time on RECBE : 8 μs

Event time window : 1 μs

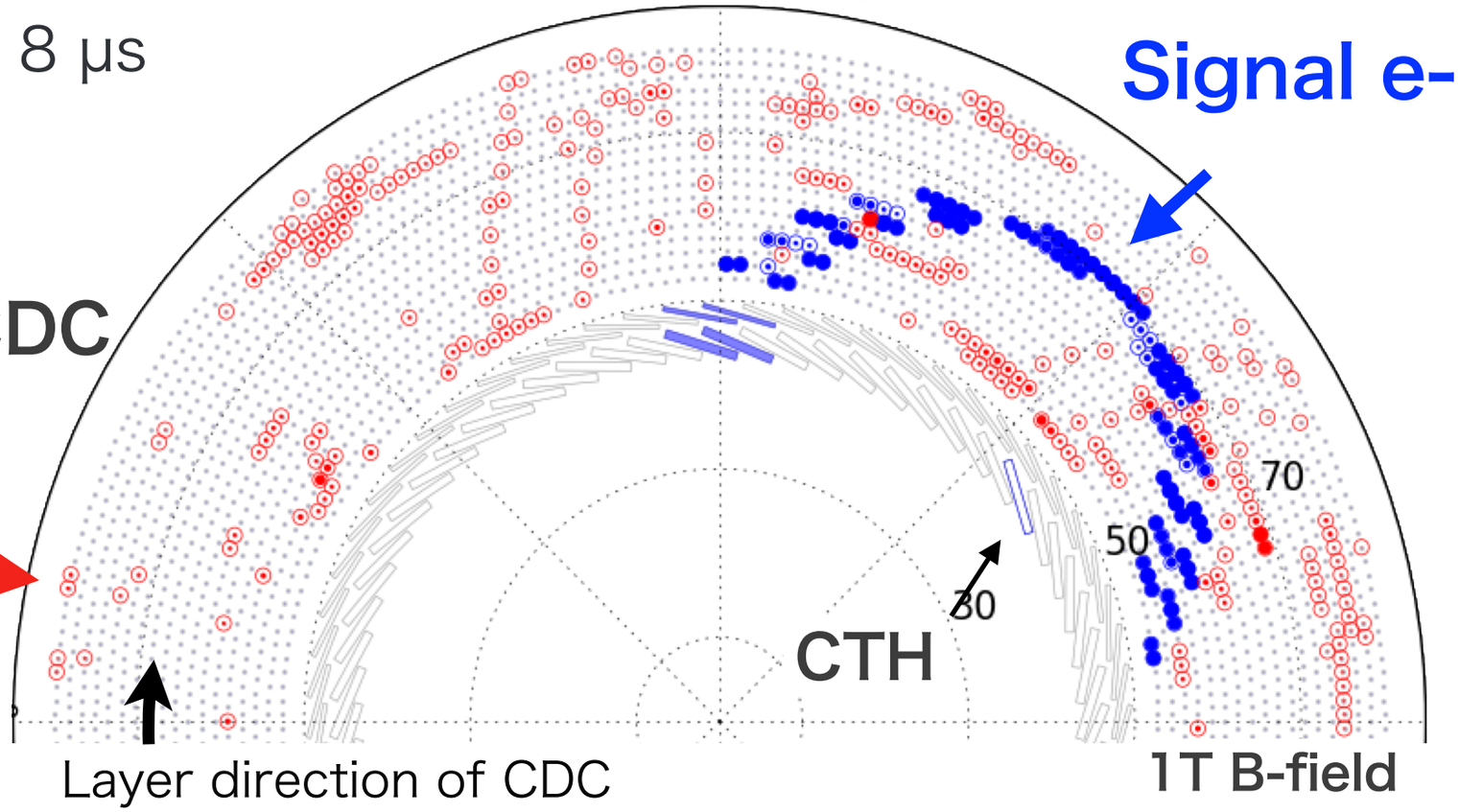
(+ 2 μs Margin)

**Efficiency : 99%**

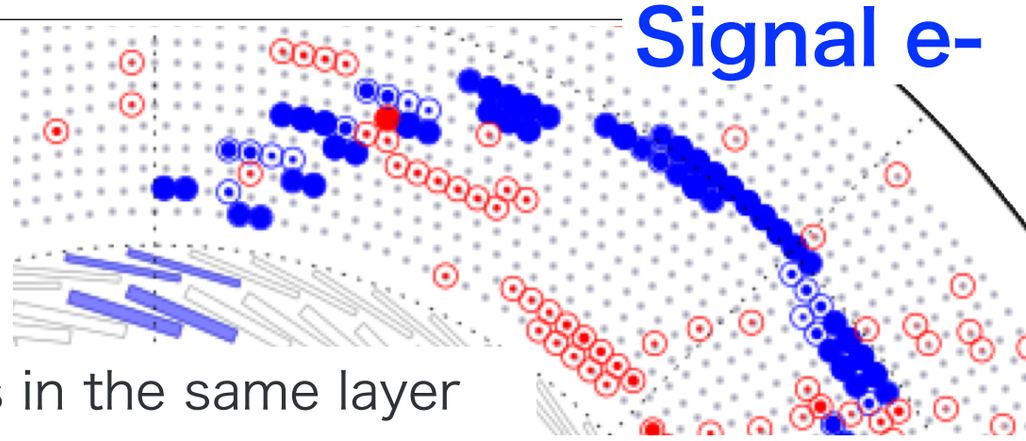
**Noise hit**

- e- (Pair-pro., Compton scattering)
- e+ (Muon capture, Pion capture)
- Proton, and so on. . .

**Hit map**



# Online classification




## Gradient Boosted Decision Tree (GBDT)

**TMVA in ROOT6**

- Features

  **Local:** Energy deposition and Layer ID

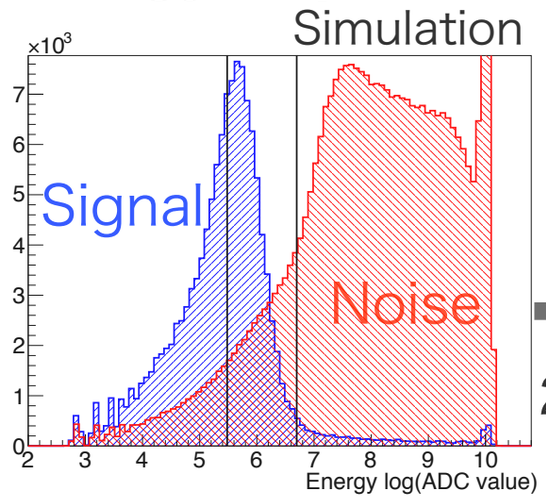
  **Neighboring:** Energy deposition on neighboring wires in the same layer

  **Global:** Data from the whole CDC wires and Relative timing from the CTH trigger

- The input-feature size is as small as possible due to the limitation from the data transfer rate for the online classification

- Look-up-tables inside a FPGA convert from the features to the GBDT outputs within a clock cycle.

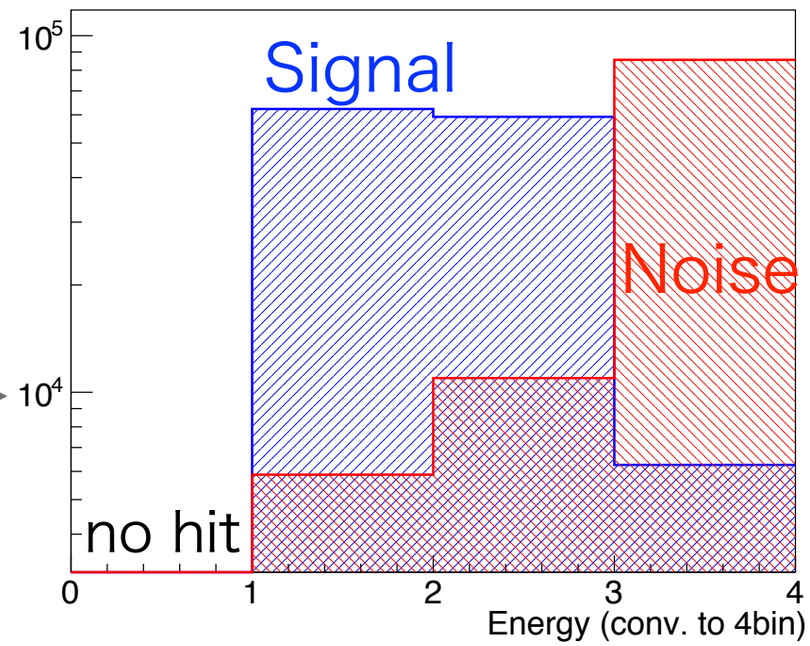
**Energy deposition**



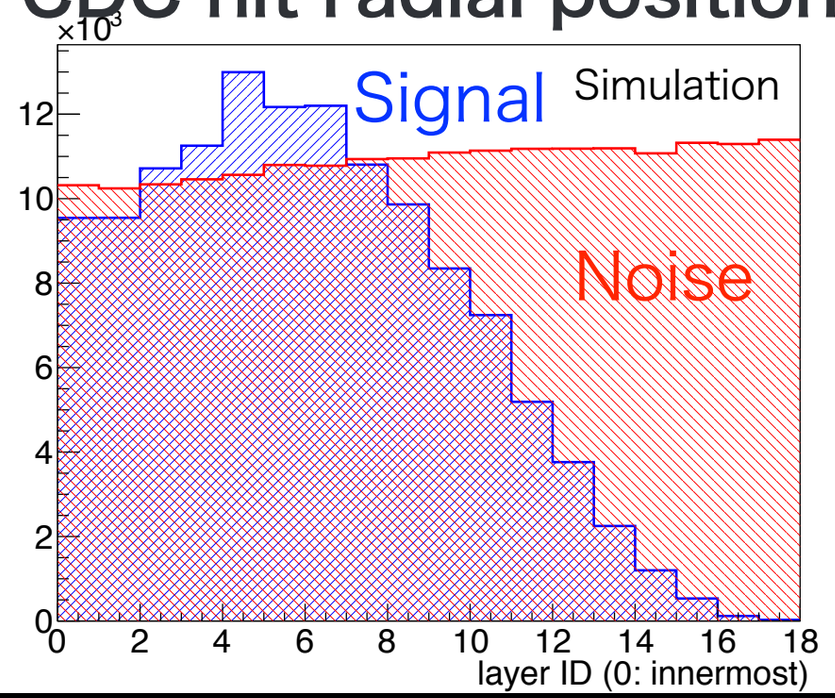

3 bin
+
No-hit

2-bit data

**2-bit Energy deposition**




**CDC hit radial position**

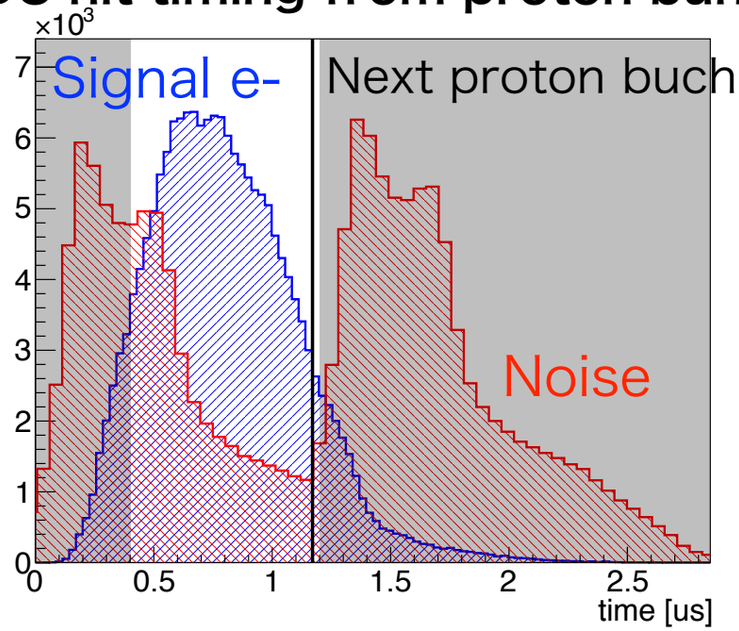


# Online classification

Preliminary

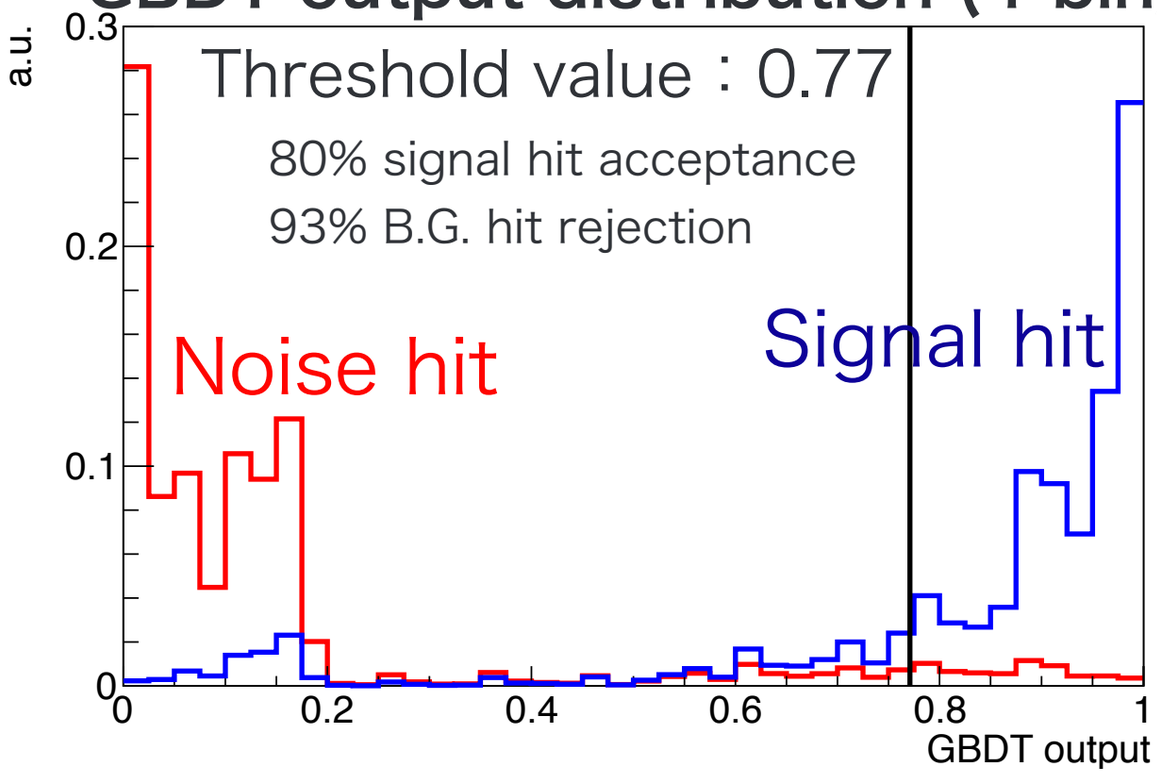
- **Trigger condition**
  - Measurement-time window
    : 0.4 ~ 1.2 μs from proton bunch
  - Integration-time window : 400 ns
    - Consider the drift time in a CDC cell
  - Sum up the GBDT outputs over threshold in the integration-time window
  - Generate a trigger signal when the total GBDT output exceeds the threshold

**CDC hit timing from proton bunch**

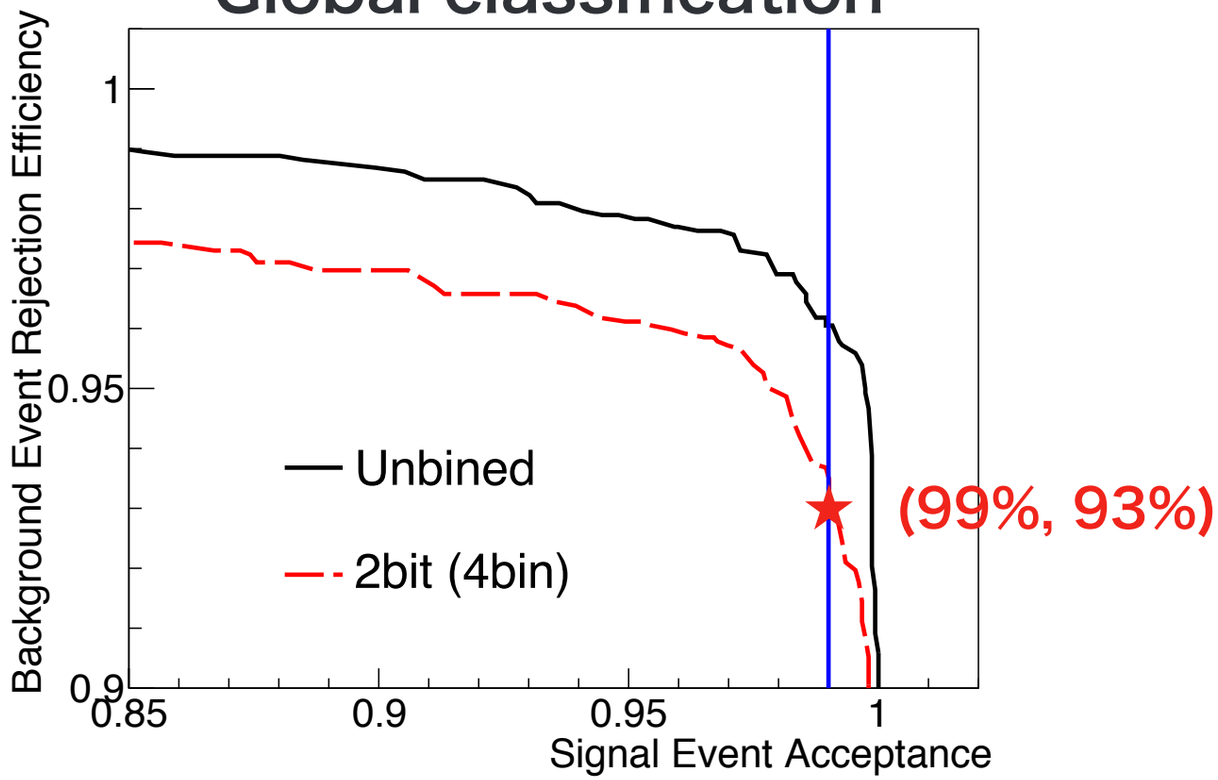



**Trigger rate (<< 24 kHz) : 27 kHz × 7% = 1.9 kHz**

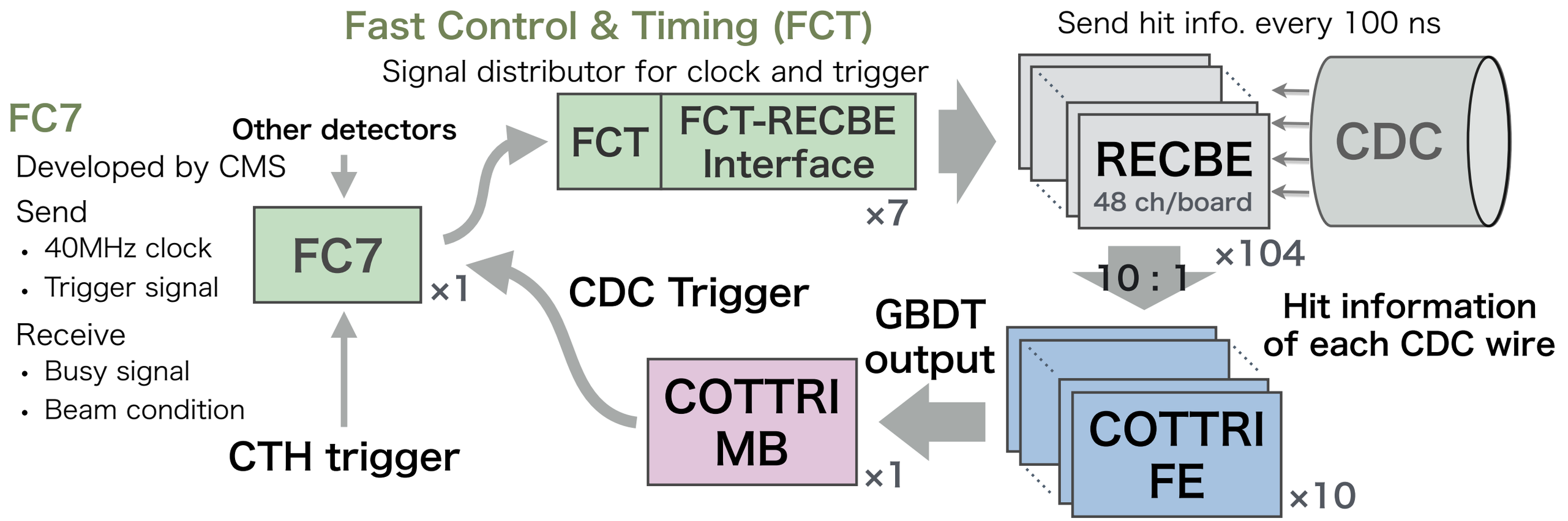
**GBDT output distribution (4-bin)**




**Global classification**



# Trigger system for CyDet




- RECBEs generate the 2-bit dE/dx information and send it every 100 ns.
- **COTTRI System**
  - **Front-end boards:** Hit classification with the Local/Neighboring features
    - Convert the 2-bit data to the GBDT output with the integration-time window of 400ns
  - **Merger-board:** Event classification with the Global feature
    - Sums up the GBDT outputs and makes the CDC-trigger decision.
- FC7 makes the final decision using both CDC and CTH trigger.

# COTTRI MB

- The first prototype of COTTRI MB was developed in 2018.
- This was also used as the prototype of COTTI CDC FE.
  - For development of the communication system between COTTRI CDC FE and RECBE.

**Kintex-7 (xc7k355tffg901)**

Logic cells: 356,160

Config. Logic Blocks: 55650 slices

Block RAM Blocks : 25740Kb

GTX: 24 lane

Max. : 12.5 Gbps/lane

**DisplayPort** ×10

TX/RX : 2 lanes ×10

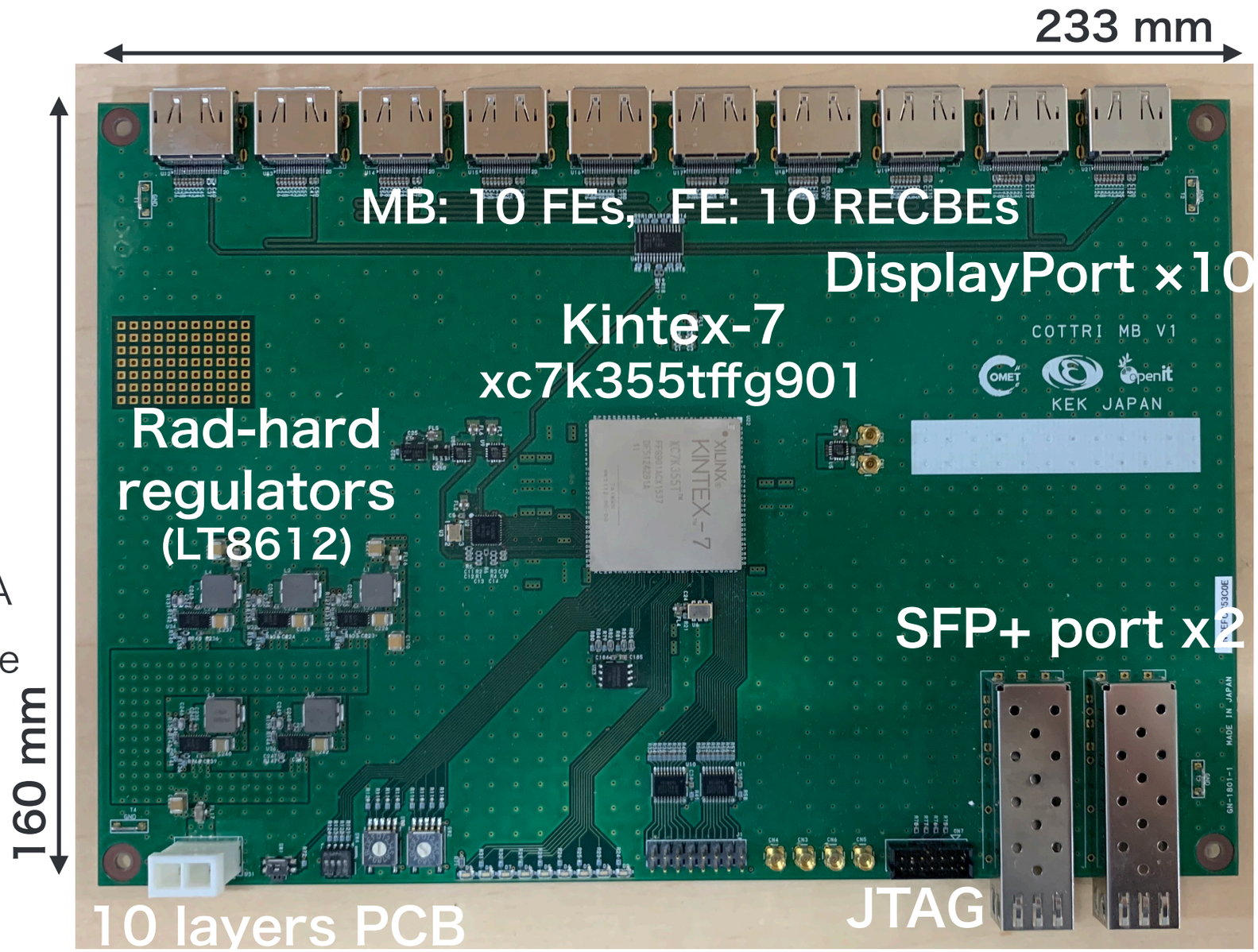
- Connect with GTX ports of FPGA

Max. data transfer rate : 5 Gbps/lane

**SFP+ port** ×2

TX/RX : 1 lane ×2

For DAQ PC and FC7



# Communication test in the winter of 2018

40MHz Clock Source

40MHz

120MHz & 40MHz

Cat7

3m

5m

RECBE x2

40MHz

Clock Distributer

DP cable

COTTRI MB

40MHz

COTTRI FE

COTTRI MB prototype is also used as the FE prototype.

# COTTRI CDC FE developed this summer

## Change from COTTRI MB

- A DP connector instead of an SFP+ socket.
- RJ45 for writing firmware
- Renge of the input voltage : 5 ~ 23 V
  - Original value : 5 ~ 6.7 V

**DisplayPort** ×11

TX/RX : 2 lanes ×11

- Connect with GTX ports of FPGA

Max. data transfer rate : 5 Gbps/lane

For 10 RECBEs and 1 COTTRI MB

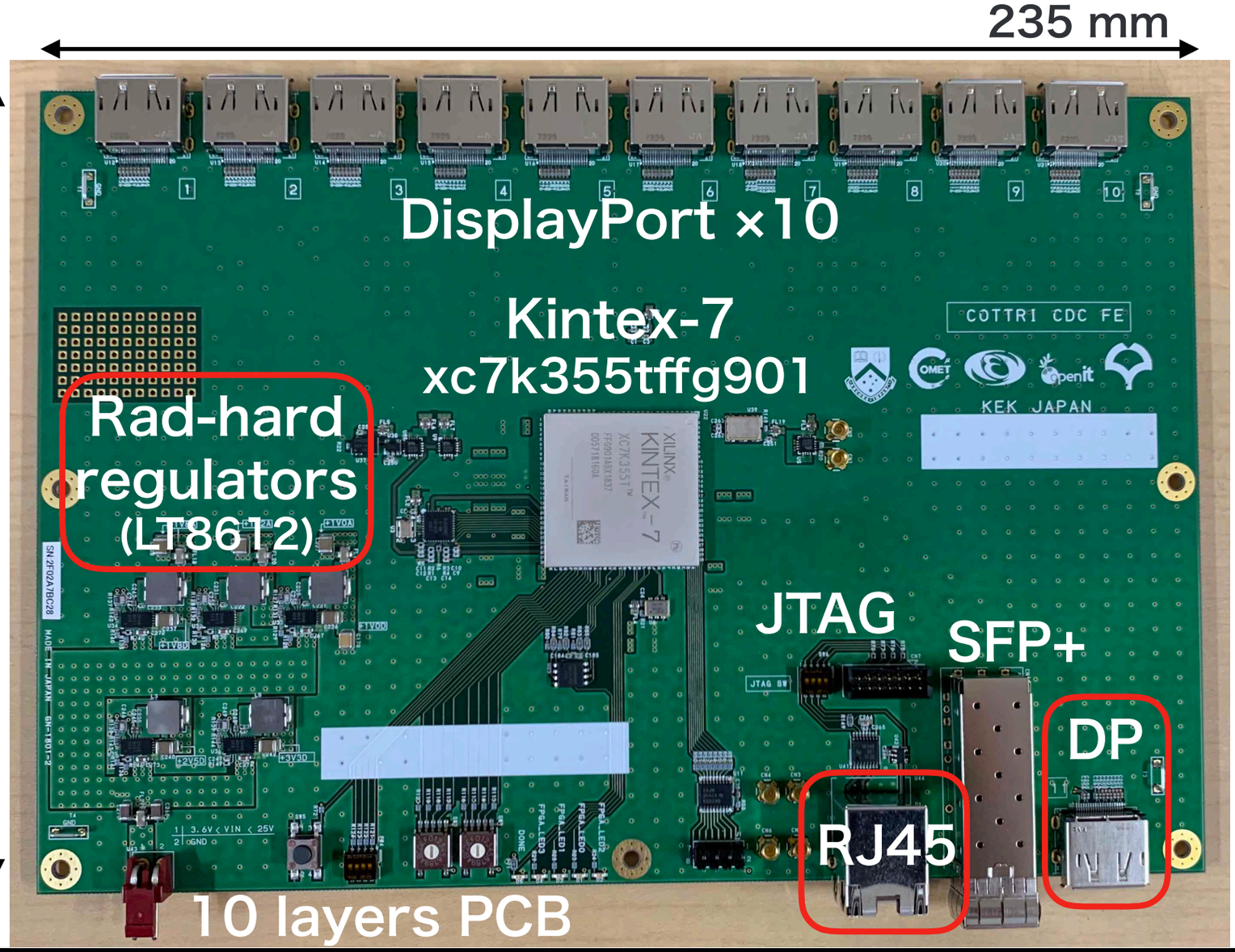
**SFP+ port**

TX/RX : 1 lane

For DAQ PC

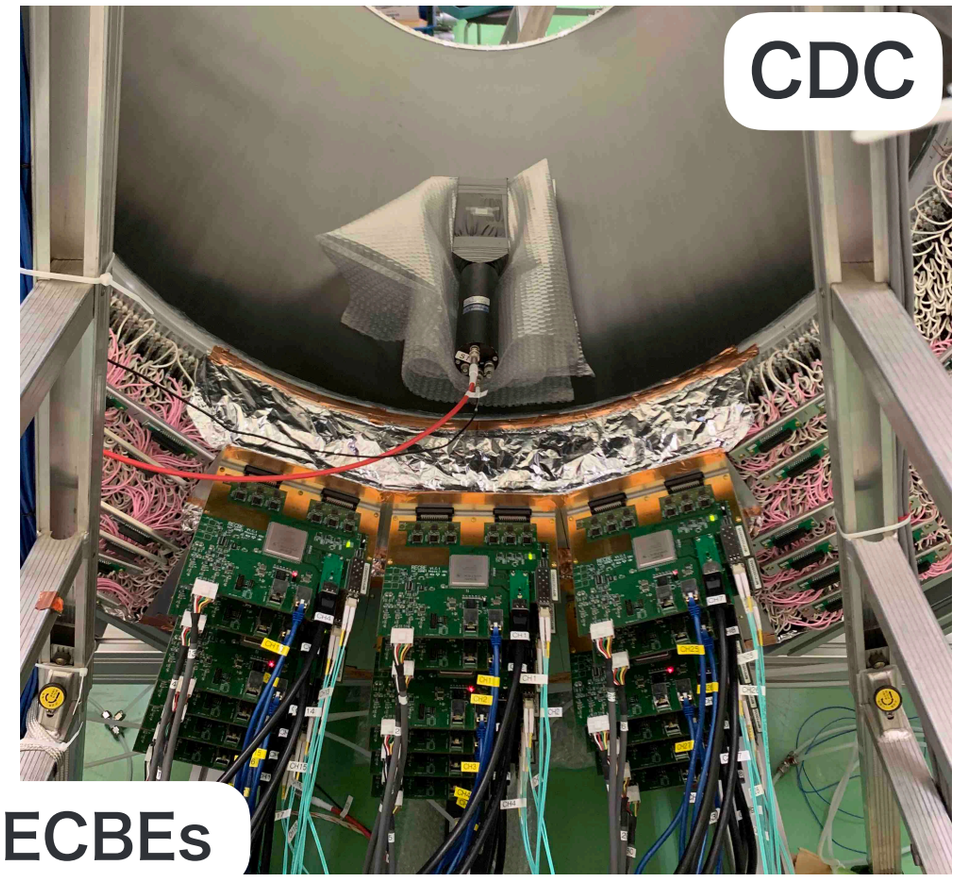
**Connector for RJ45**

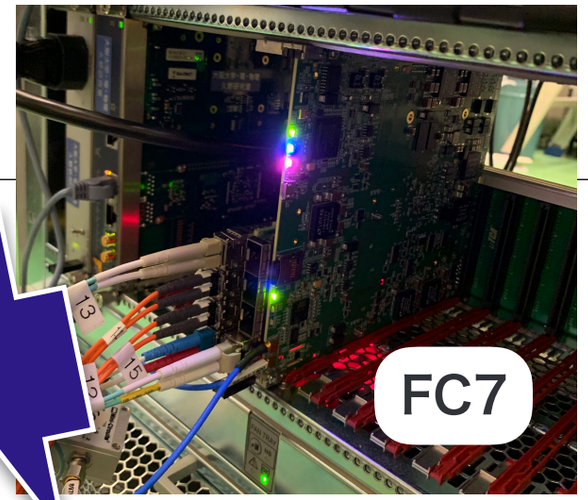
for writing firmware



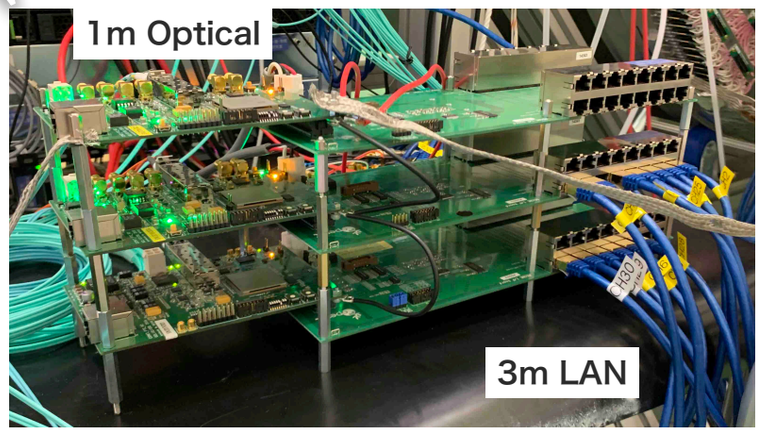
# Setup

- Trigger condition
  - CDC self-trigger
  - 2 scintillation counters
- (tentative) DAQ: DAQ Middleware
  - for RECBEs, COTTRI CDC FE, and COTTRI MB
- **Data acquisition with using both the CDC self-trigger and the scintillation counters was succeeded.**
  - Counting the number of CDC hits
- The data analysis is ongoing.

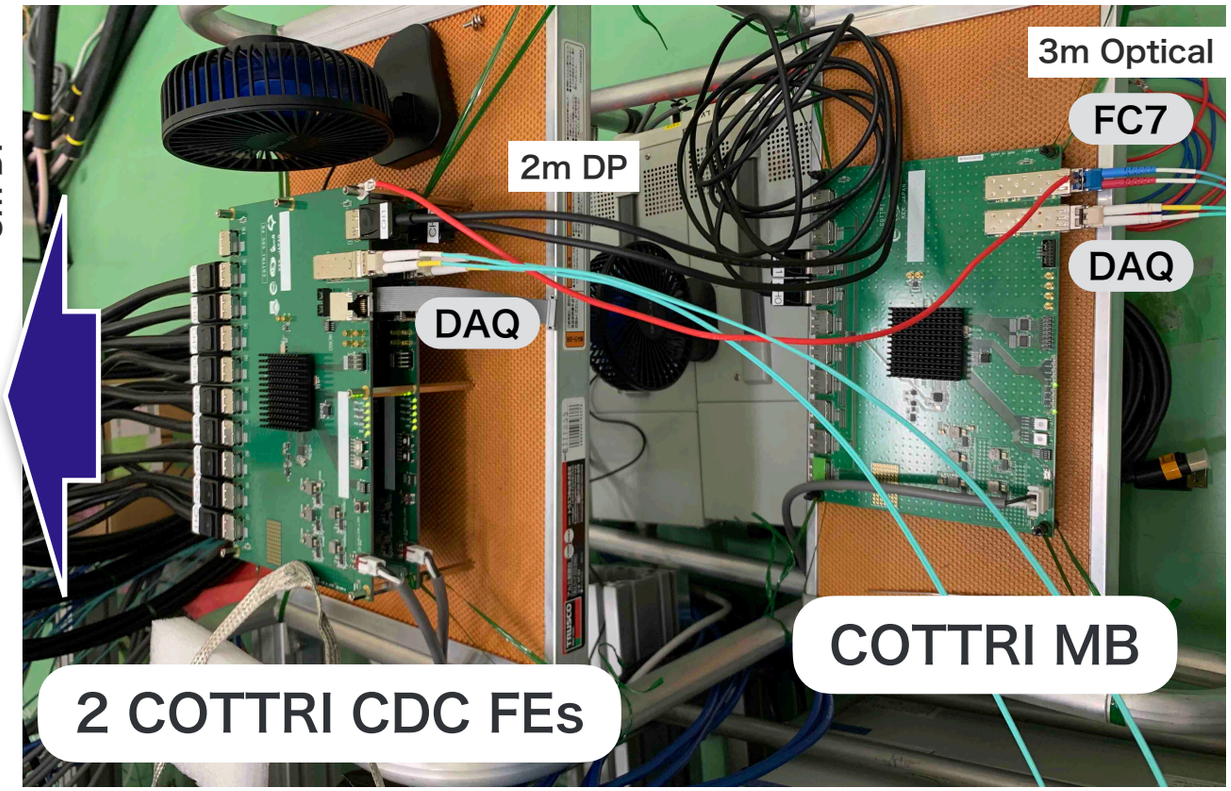



FCT & COTTRI




FCT &
FCT RECBE I/F
(2 sets)

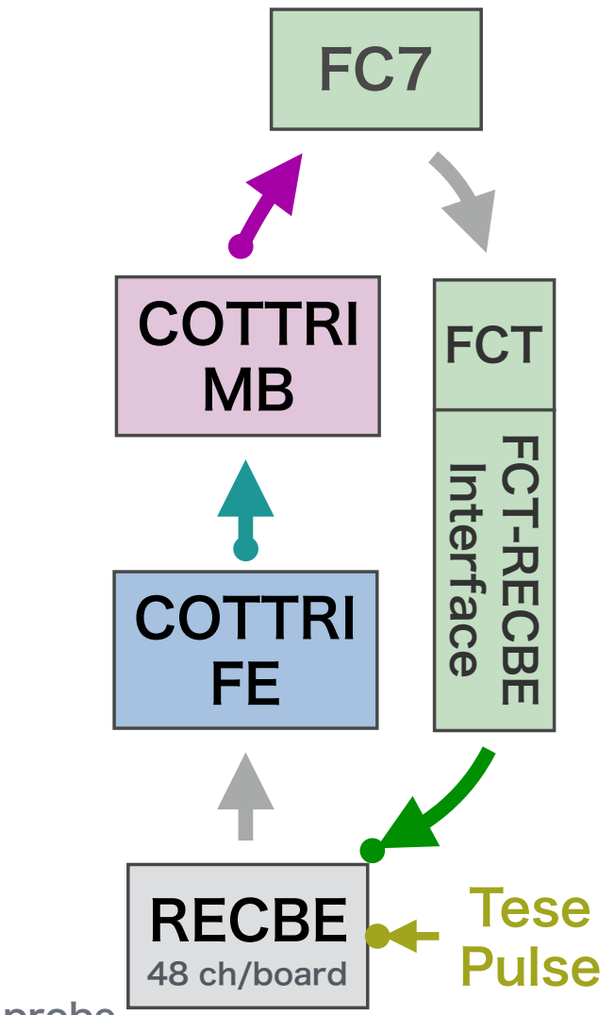


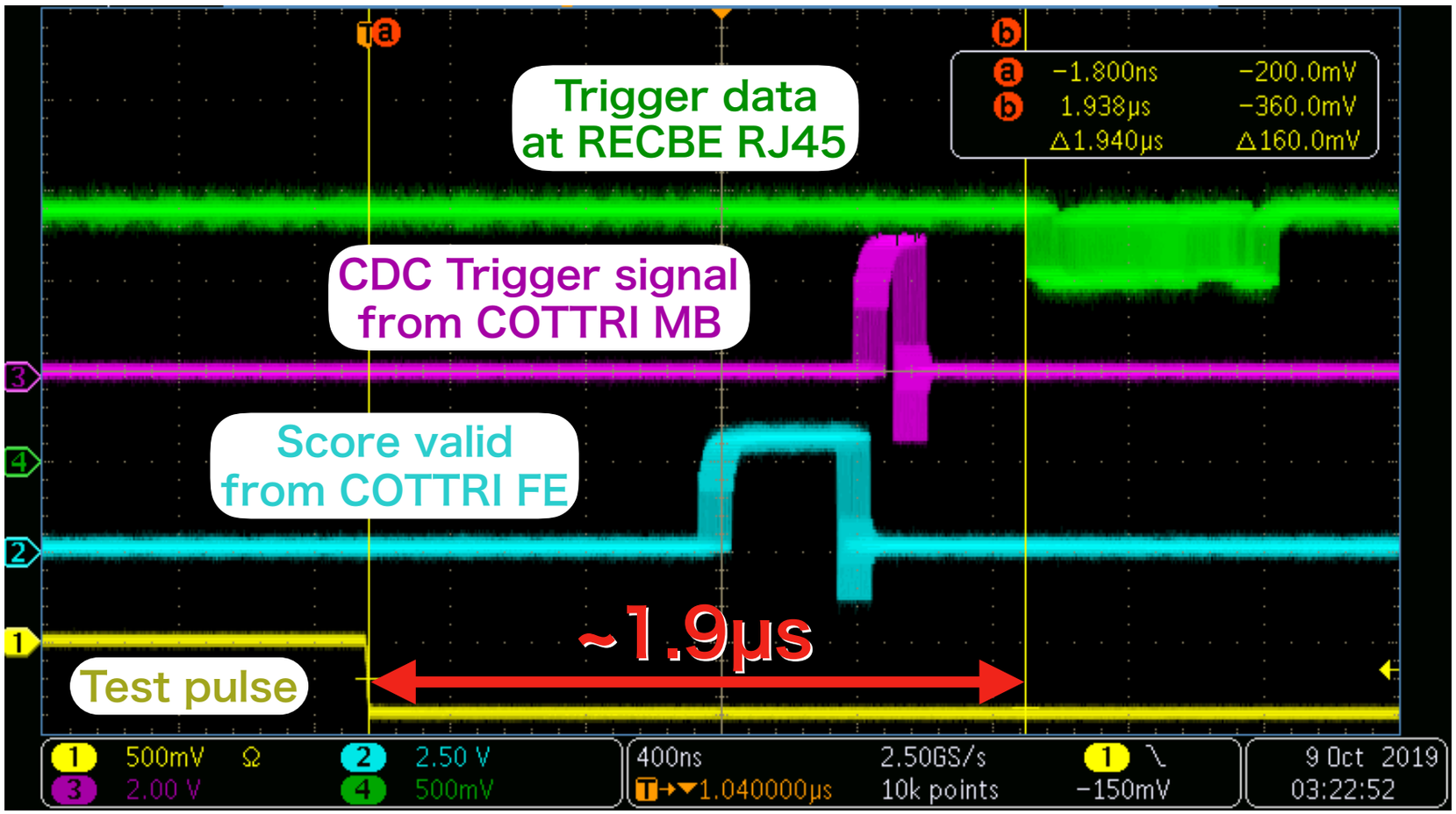
# Latency

**Requirement : <5 μs**

**Total : 3.1 - 3.2 μs**

| | Latency [μs] | Description |
|---|---|---|
| RECBE - COTTRI System - FC7 - RECBE | 1.9 - 2.0 | 100ns fluctuation by the data transfer rate of 10MHz |
| Drift time distribution | ~0.4 | Data evaluation every 100ns |
| Trigger receiving time in RECBE | 0.8 | 32bit trig. data with 40MHz |

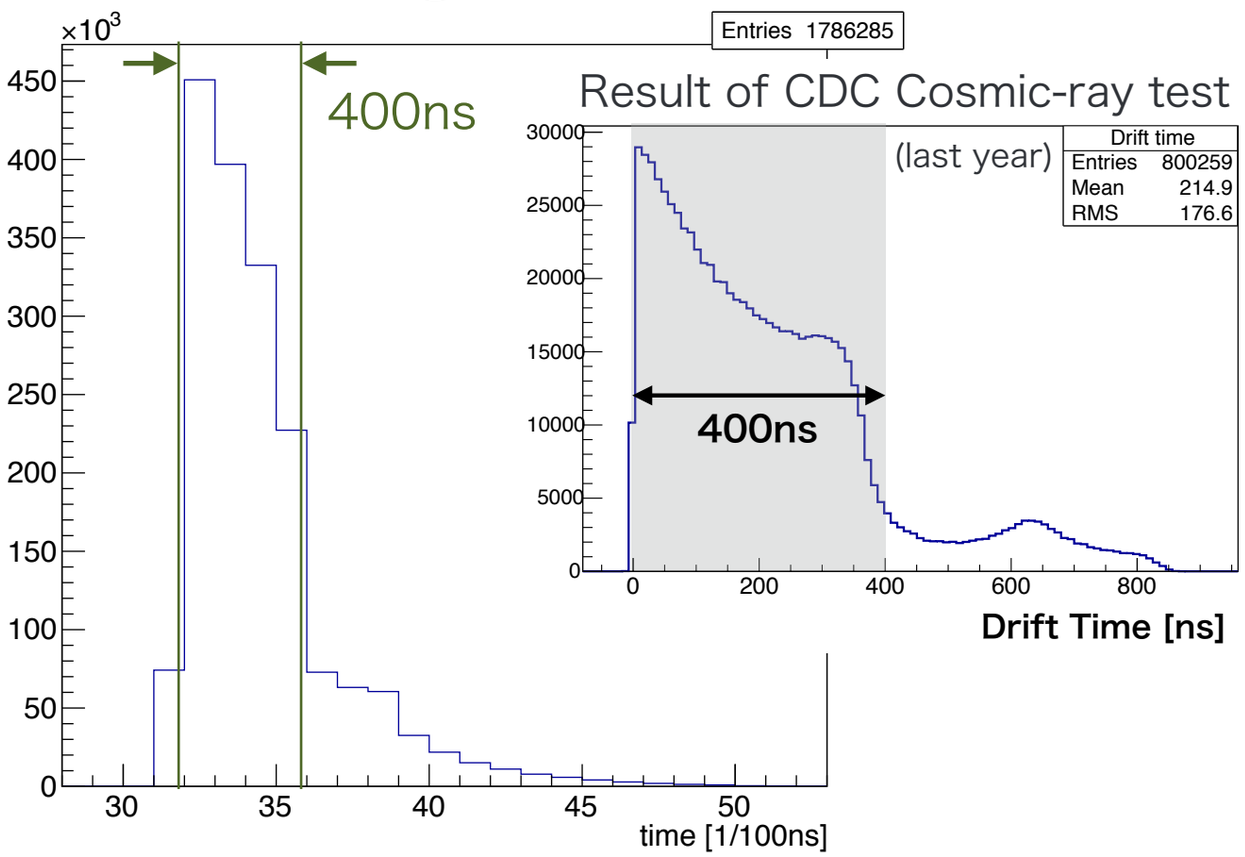


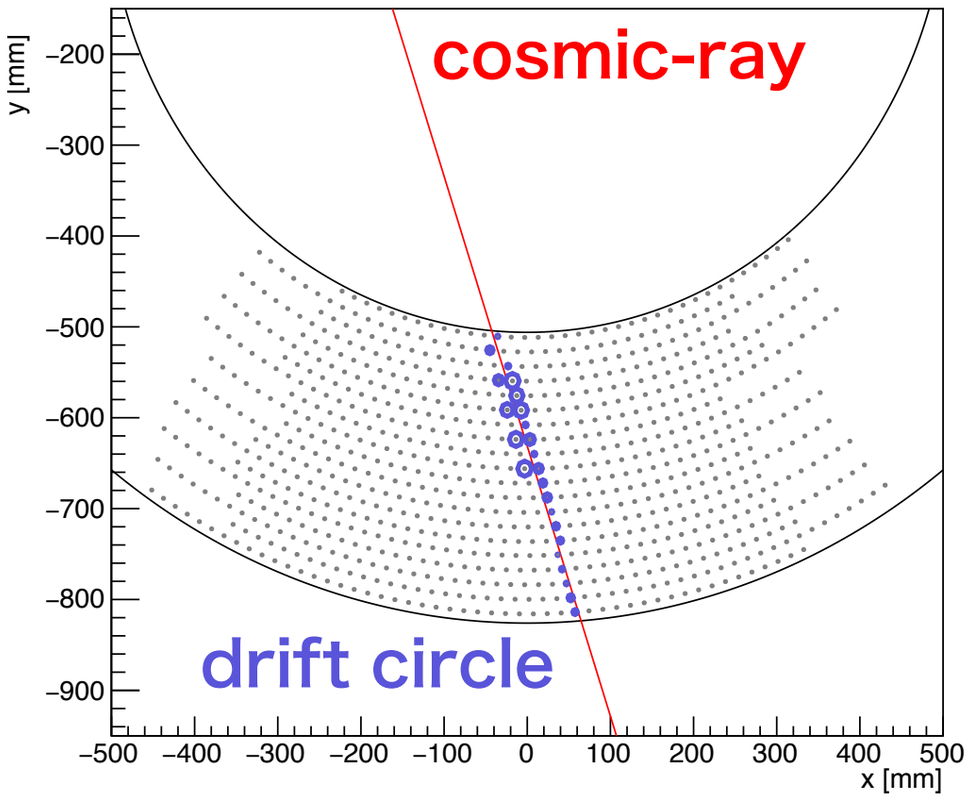
# Cosmic-ray test: Result

- The hit-timing distribution from the COTTRI data is the same shape as the drift-time distribution from the CDC cosmic-ray data.
- Tracking the cosmic-ray events was succeeded using the data from CDC and the timing counters, which was taken with the fast-online trigger system.

**Hit timing distribution**




**Event display**



# Summary & prospects

- COMET Phase-I : Search for neutrino-less μ-e conversion in Al
- Trigger rate reduction is very important for the stable operation

  Trigger rate: <24 kHz,  Efficiency: 99%,  Latency: <5 μs

## Hardware development

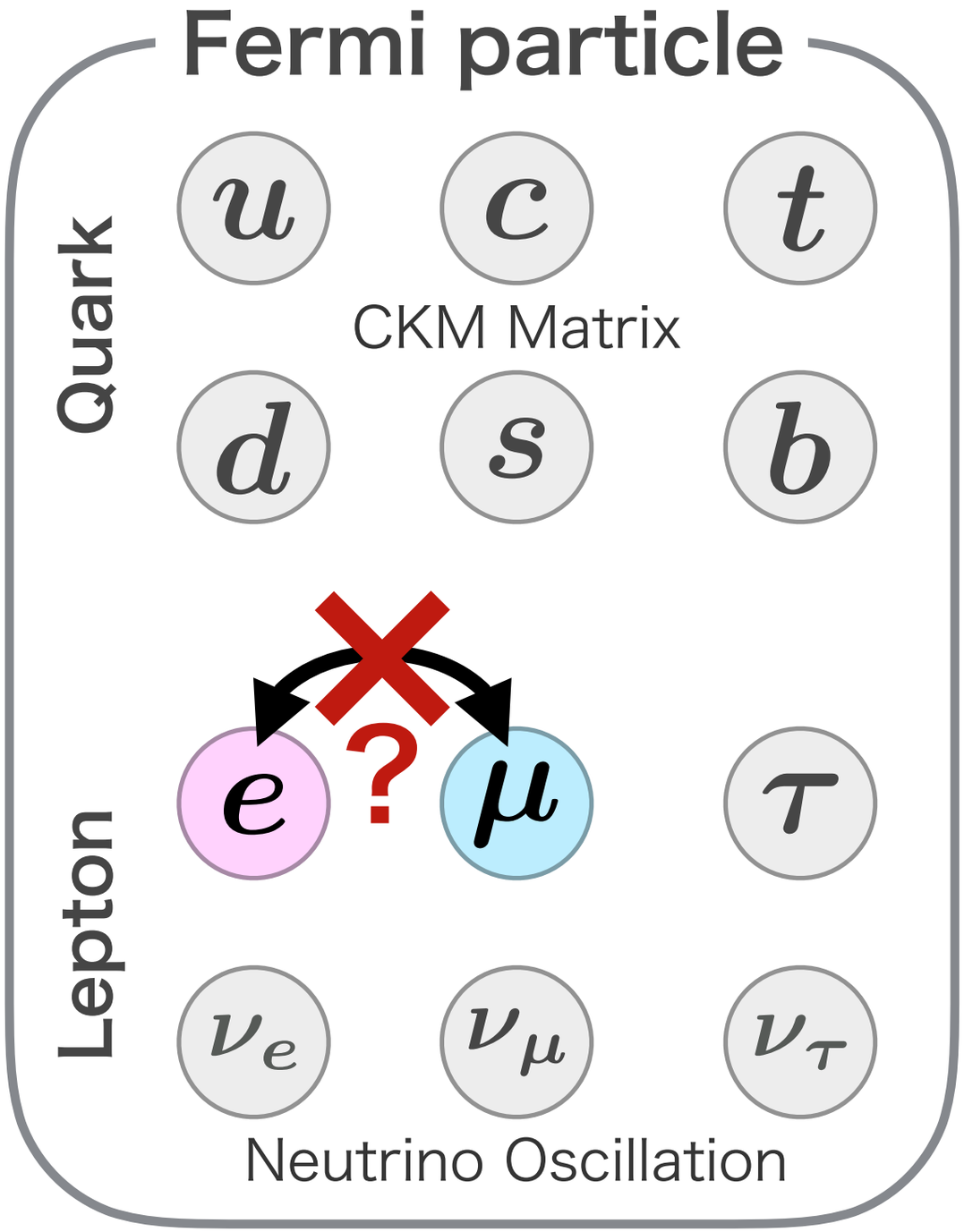
- The prototypes of both COTTRI CDC FE and COTTRI MB were developed.
- Data acquisition with using the COTTRI system in a part of the CDC setup was successfully done.
  - Total latency was measured to be 3.2 μs.
  - Cosmic-ray tracks were reconstructed.

## Prospects

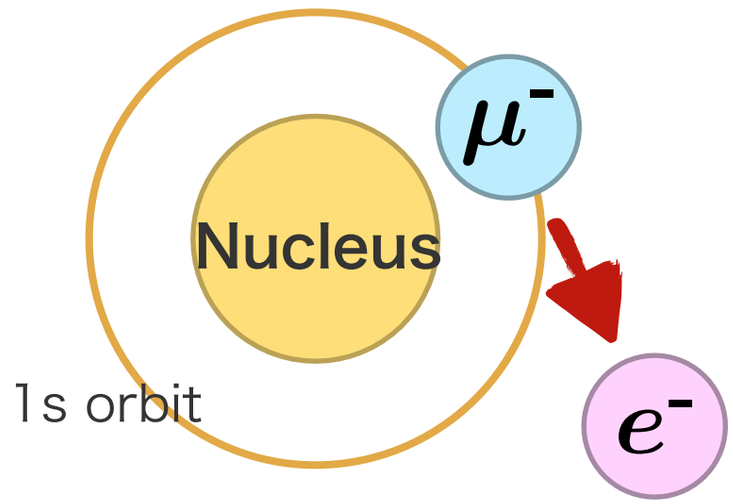
- Evaluate the trigger efficiency of the system.
- Optimize the parameters such as the time window, the threshold values for the classification by applying simulation data of COMET Phase-I.

# Backup

# Muon to electron conversion




Muonic atom




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

**μ-e conversion**

**(Charged Lepton Flavor Violation)**

**Branching ratio ( $\mu \rightarrow e\gamma$ )**

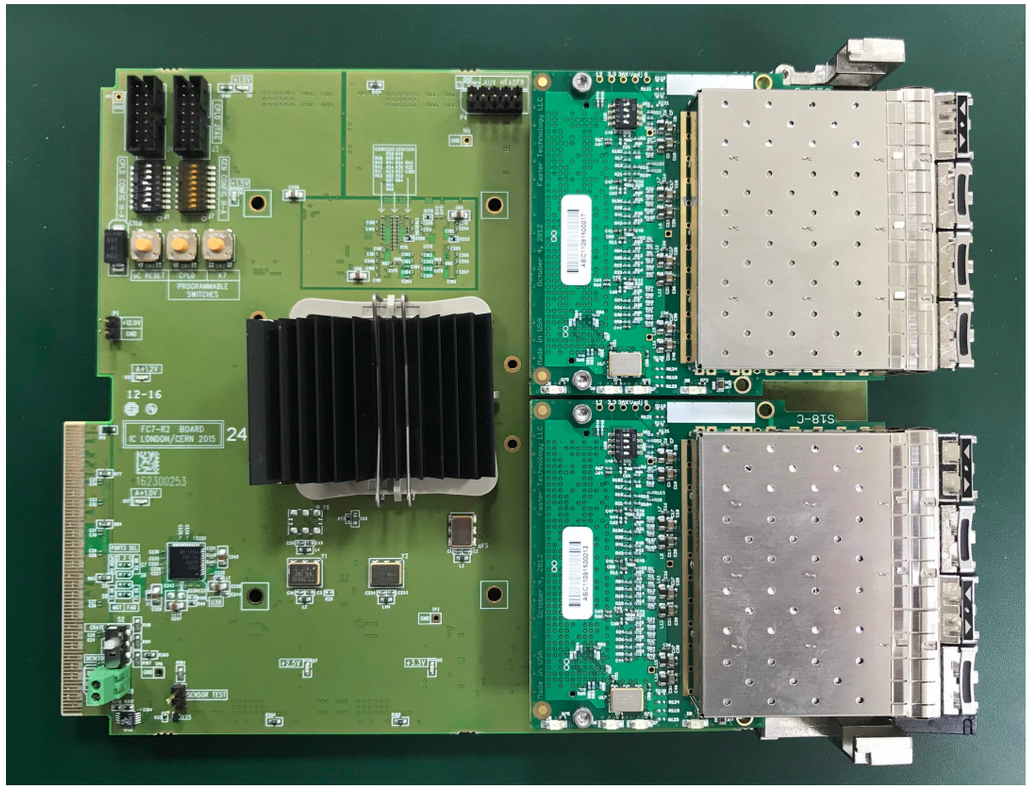
Standard Model : $O\left(10^{-54}\right)$

Beyond the SM : $O\left(10^{-15 \sim -17}\right)$

**Observation of μ-e conversion would indicate new physics!!**

# FC7

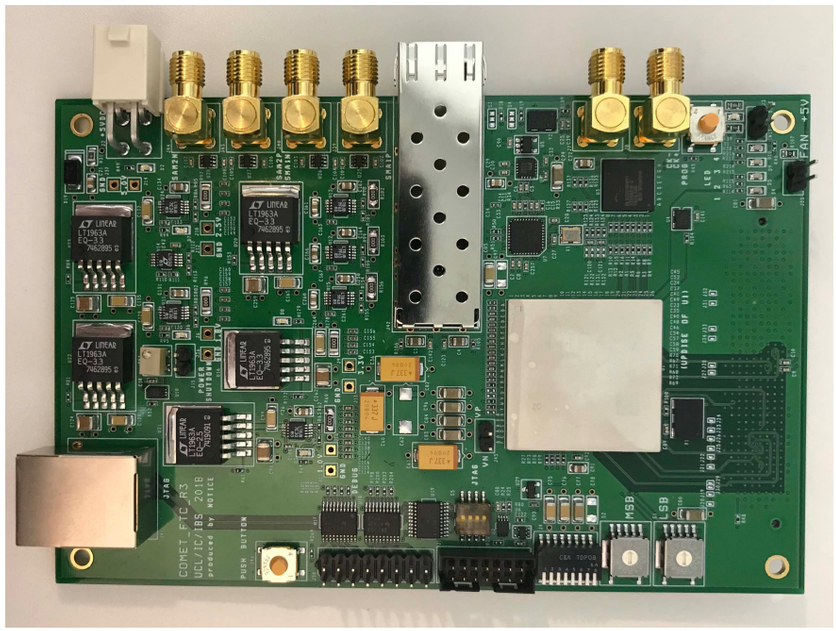
- Design for use at CMS by CERN
- Specification
  - Xilinx Kintex-7
  - 20 serial MGT links
    - Multi-gigabit data transfer
  - 2 FMC for mezzanine cards
    - A mezzanine card has 8 SFP+ cages




- Purpose
  - Source of fast control signal distribution
    - 40 MHz common clock
    - Trigger

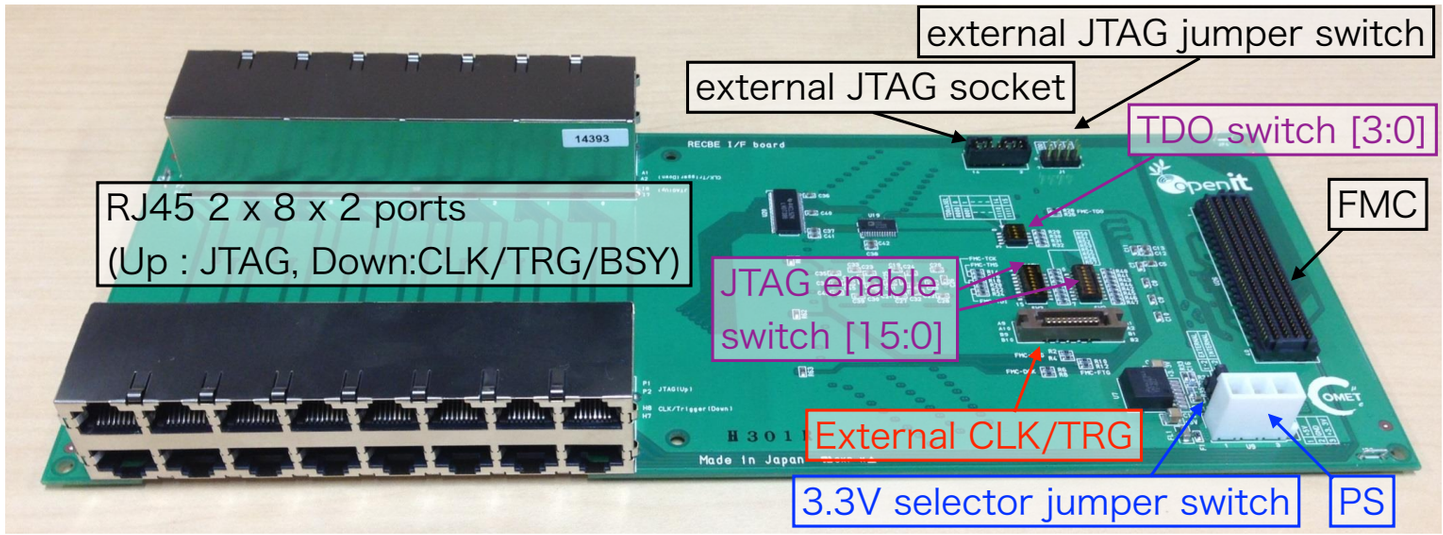
# Fast Control and Timing (FCT) board

- Specification
  - Xilinx Kintex-7
  - FC7 MGT links
- Purpose
  - Connection between FC7 and Front-end boards
  - Fast control signal distribution
    - 40 MHz common clock
    - Trigger
  - Firmware download
  - Busy signal receiver



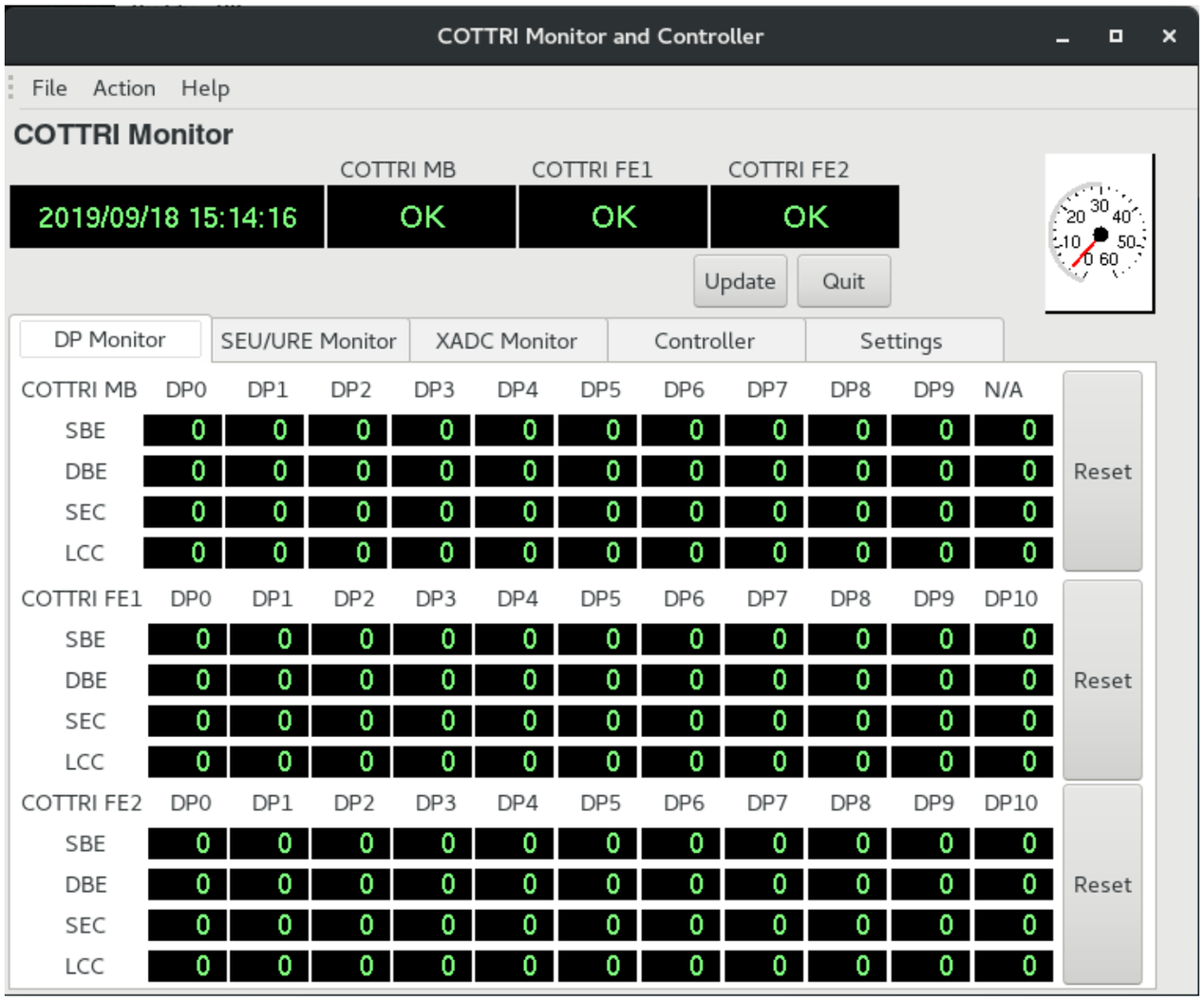
**FCT**

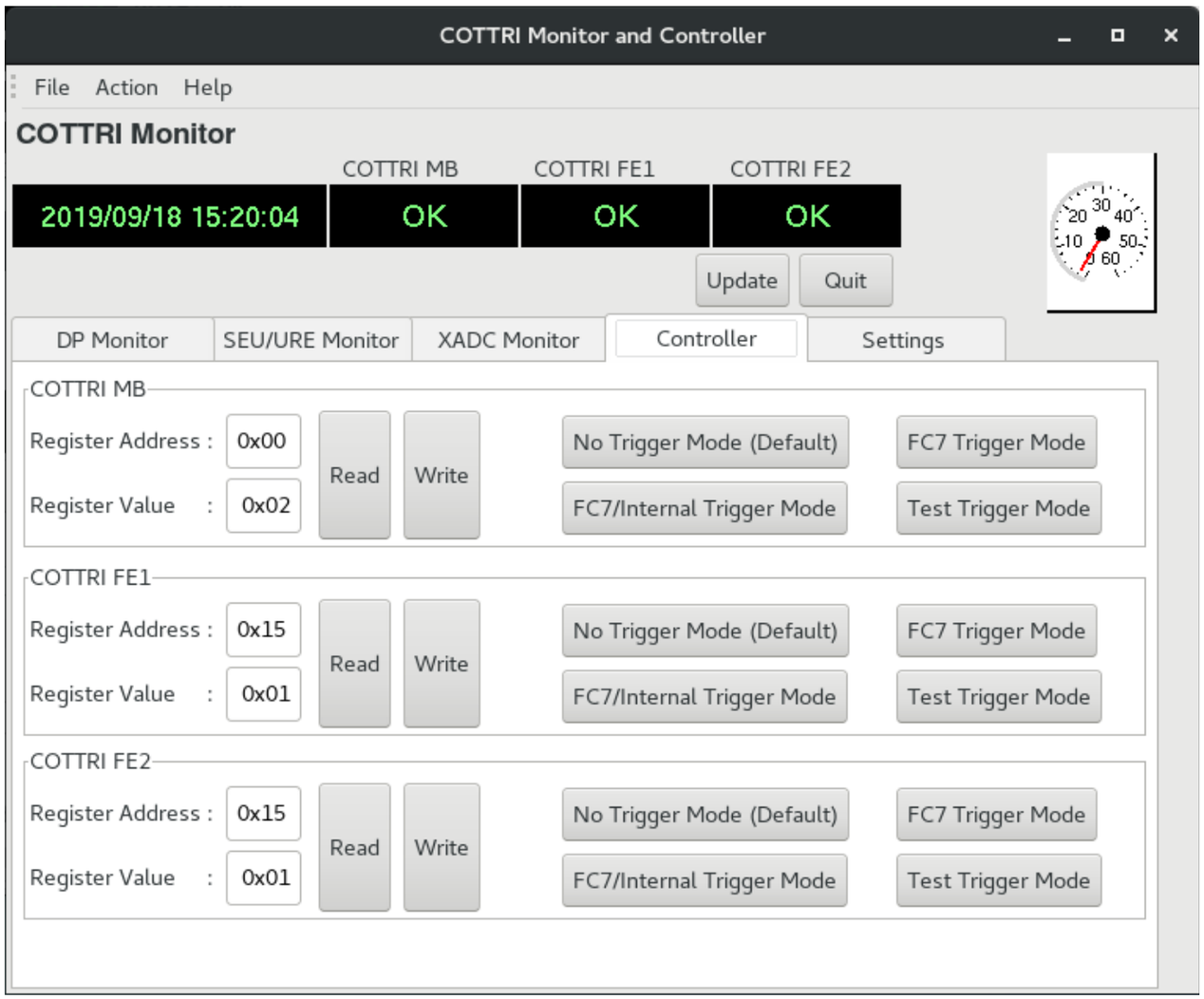
## FCT RECBE Interface



# Done: Monitor & Control (by Hisataka)

- KiNOKO
- Monitor
  - Communication errors, SEM, Temperature, and Input voltage
- Can read and write register values

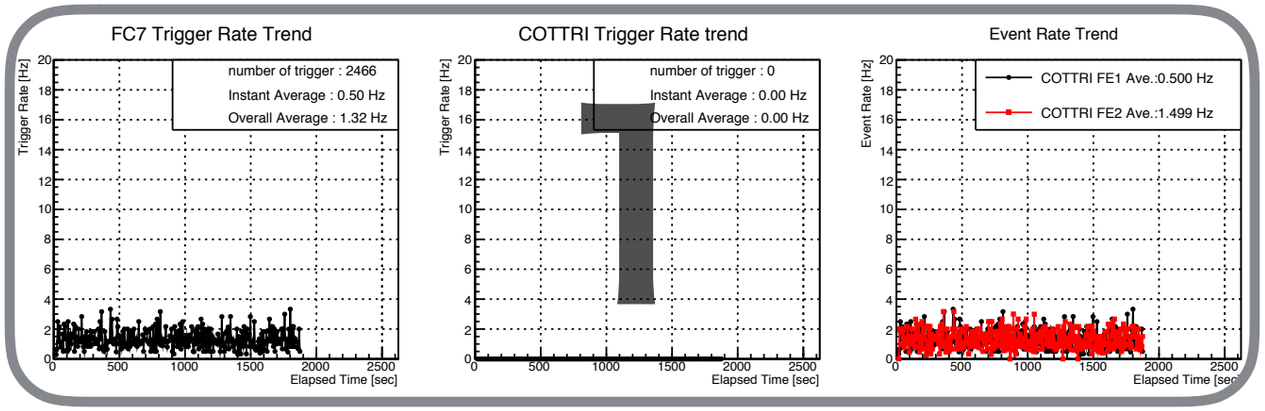


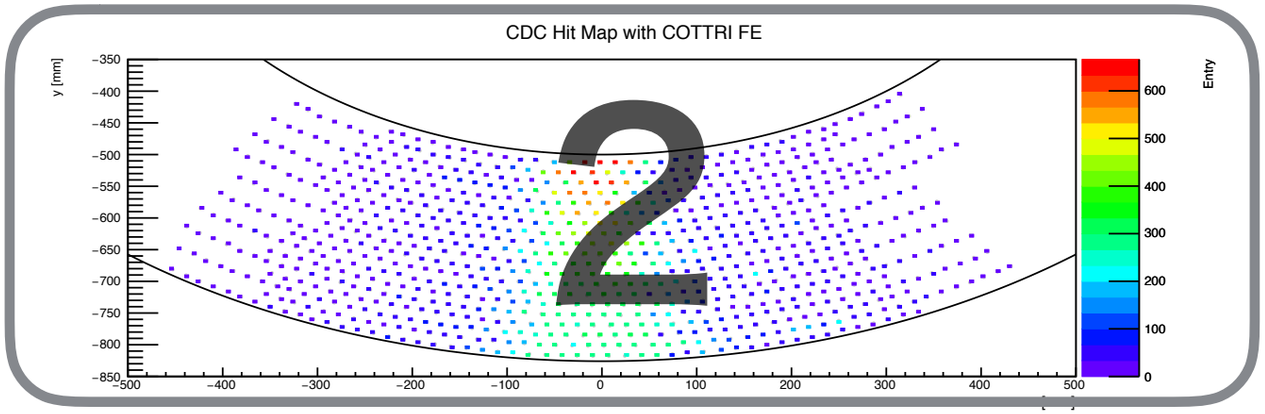



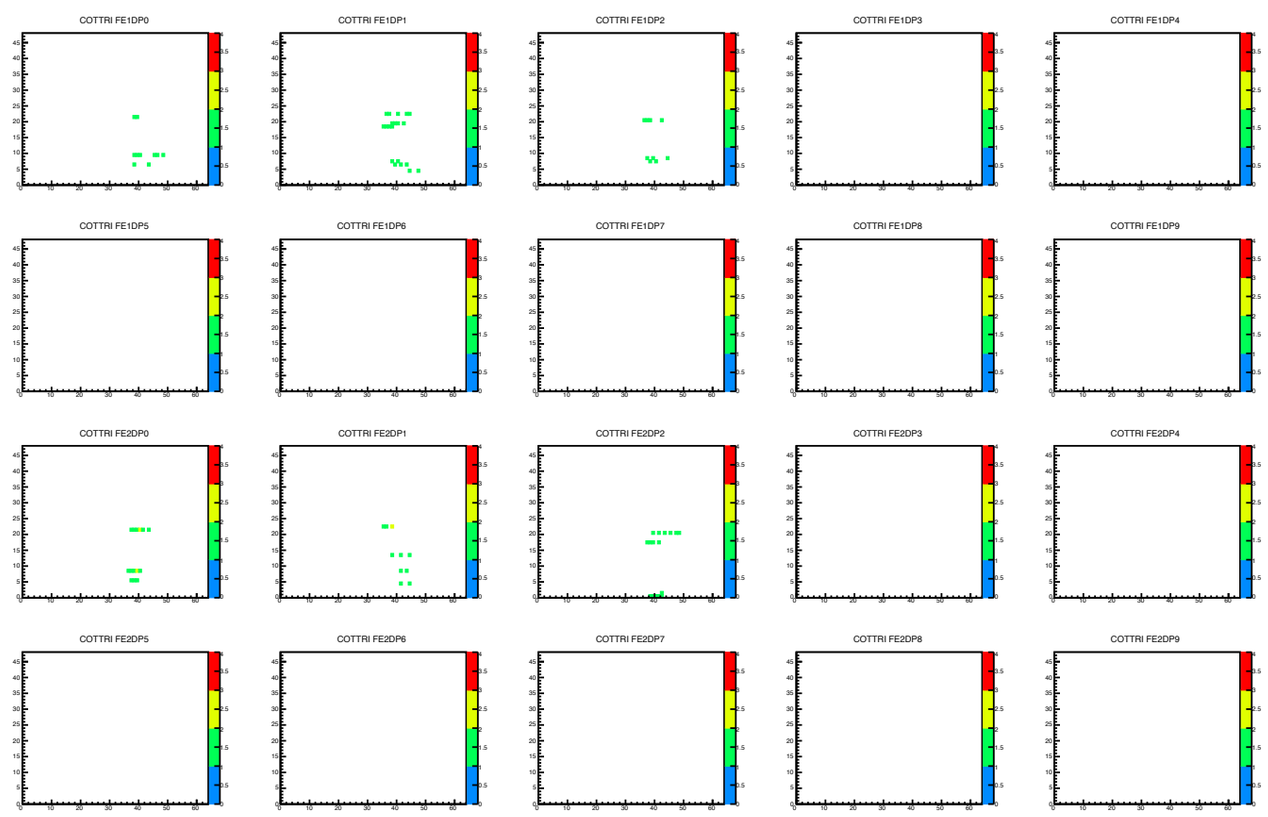
# Done: DAQ (by Hisataka)

- DAQMW for CDC FE
- Monitor
  1. Event rate
  2. Hit map
  3. Timing distribution of hits (event-by-event)

3

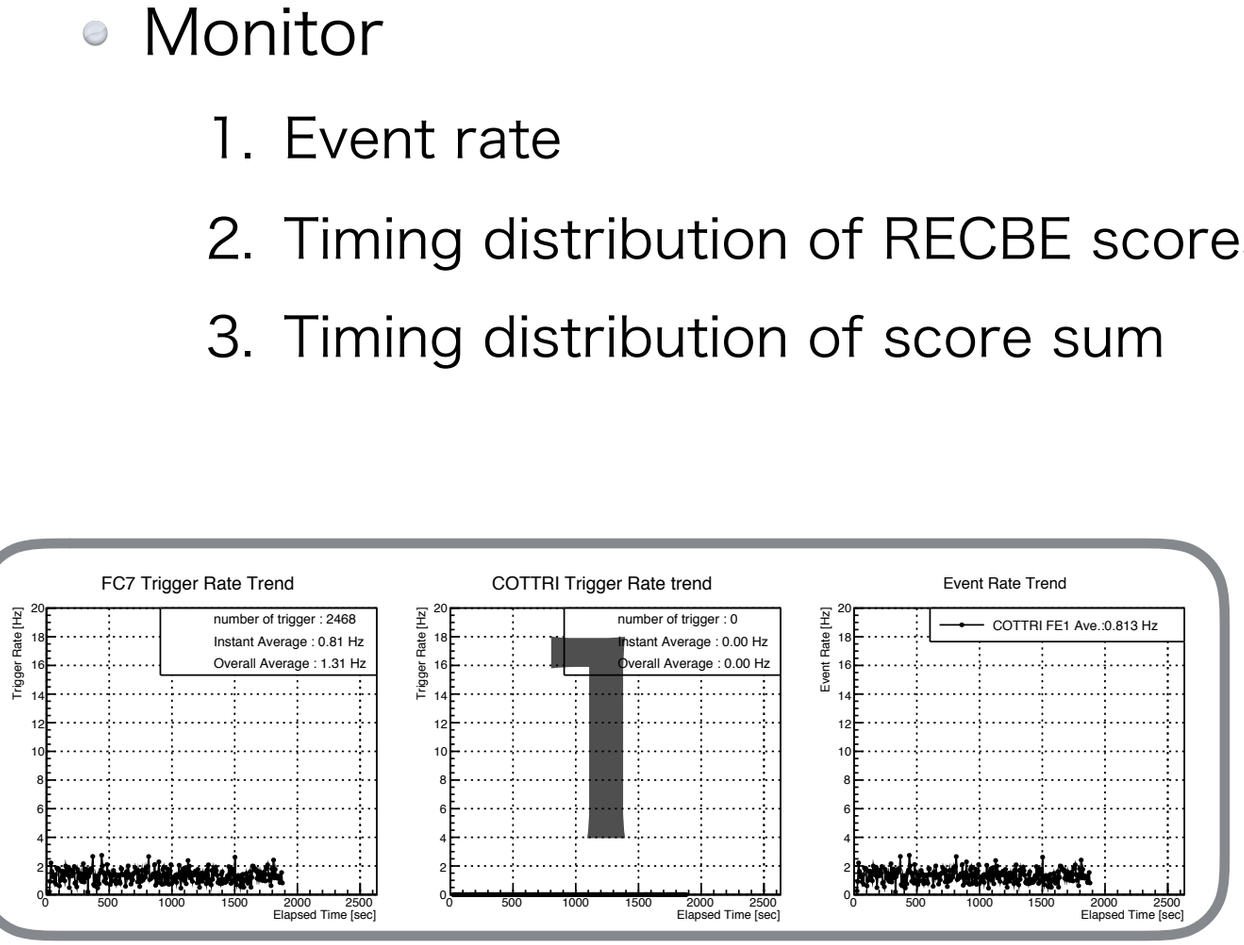


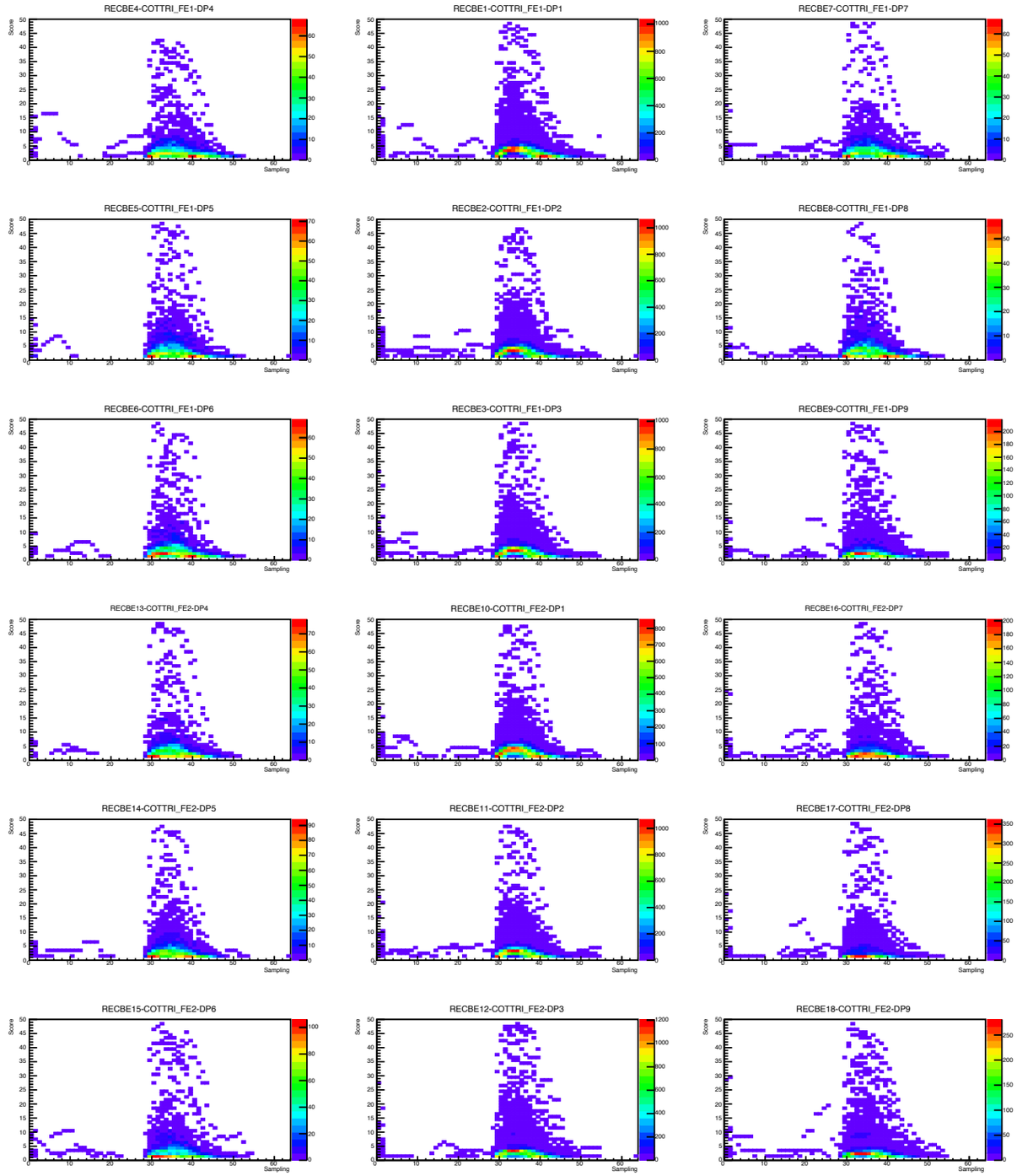
# Done: DAQ (by Hisataka)

- DAQMW for MB
- Monitor
  1. Event rate
  2. Timing distribution of RECBE scores
  3. Timing distribution of score sum



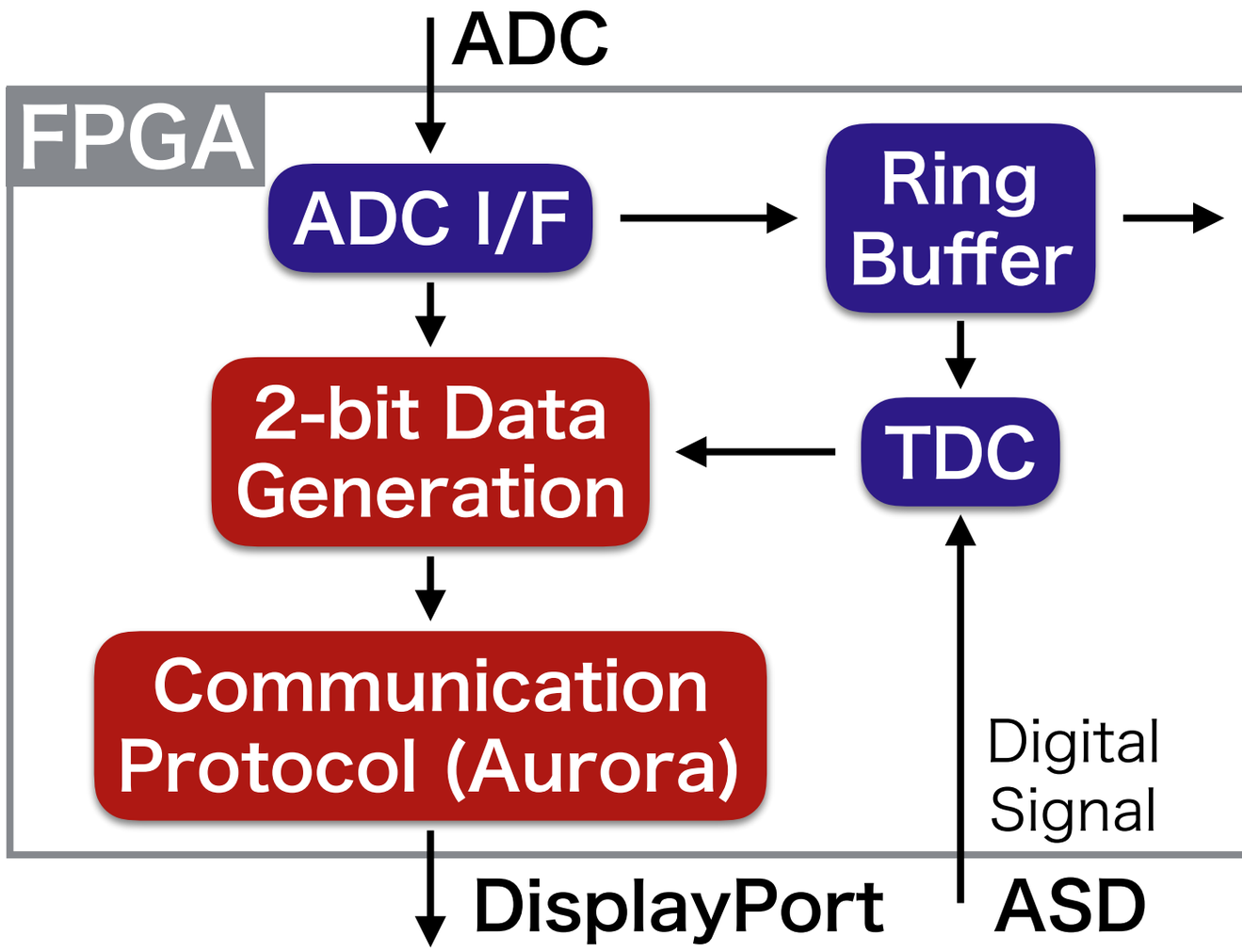






# 2-bit ADC data generation in RECBE

- Convert energy deposition to 2-bit
  - Sum up every 3 ADC samplings (every 100ns)
  - Without TDC hit, 2-bit data is “0”
  - Summed ADC is divided into 3 regions by using 2 thresholds. (“1”, “2” or “3”)
- Send 2-bit data to COTTRI FE
  - Aurora 8B/10B IP Core
  - 4.8 Gbps/lane w/ 120MHz GT clock
  - ECC module (Tai original)
    - 6 parity bits for 24-bit




## Data format for the trigger system

| Bit | 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Header | 0 | Parity bits | | | | | | 1 | Sent number | | | | | | | | | | | | | | | | Board ID | | | | | | | |
| 2-bit data | 0 | Parity bits | | | | | | 0 | ch11 | ← | | | | | | | | | | | | | | | | | | | | | 0 | |
| | 0 | Parity bits | | | | | | 0 | ch23 | ← | | | | | | | | | | | | | | | | | | | | | 12 | |
| | 0 | Parity bits | | | | | | 0 | ch35 | ← | | | | | | | | | | | | | | | | | | | | | 24 | |
| | 0 | Parity bits | | | | | | 0 | ch47 | ← | | | | | | | | | | | | | | | | | | | | | 36 | |

# Communication stability

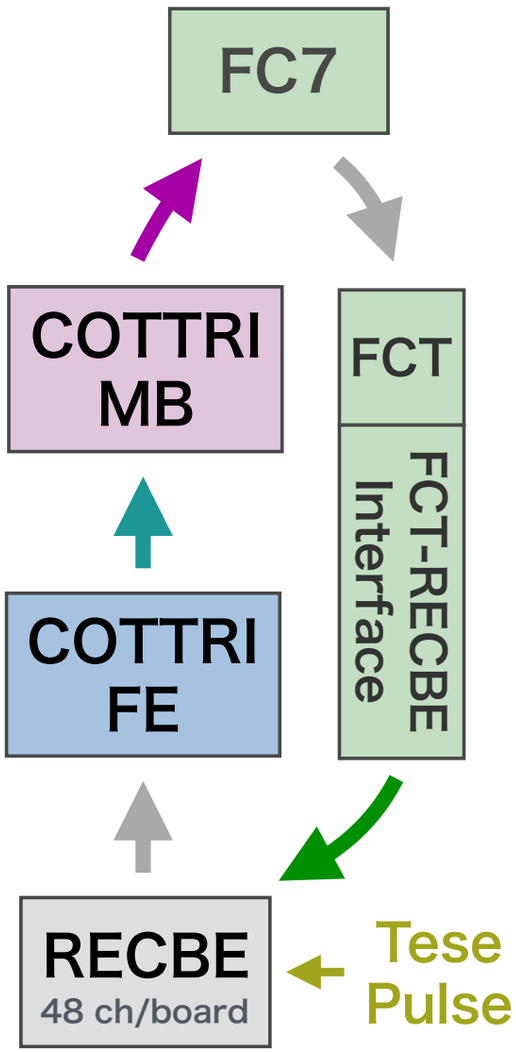
- Running time: 2 days
- Data type: constant data
- Result: no lost connection and no data error
  - Single bit error and double bits error has never been observed without radiations.
  - Error rate: <3.6 x $10^{-15}$ error/bit
- Error rate by neutrons
  - The accelerator condition was very bad in the previous  beam test in this month.
  - Only one setup was tested.
    - RECBE communicated with COTTRI FE while only RECBE was exposed to neutrons.
    - Tai is analyzing the data now.

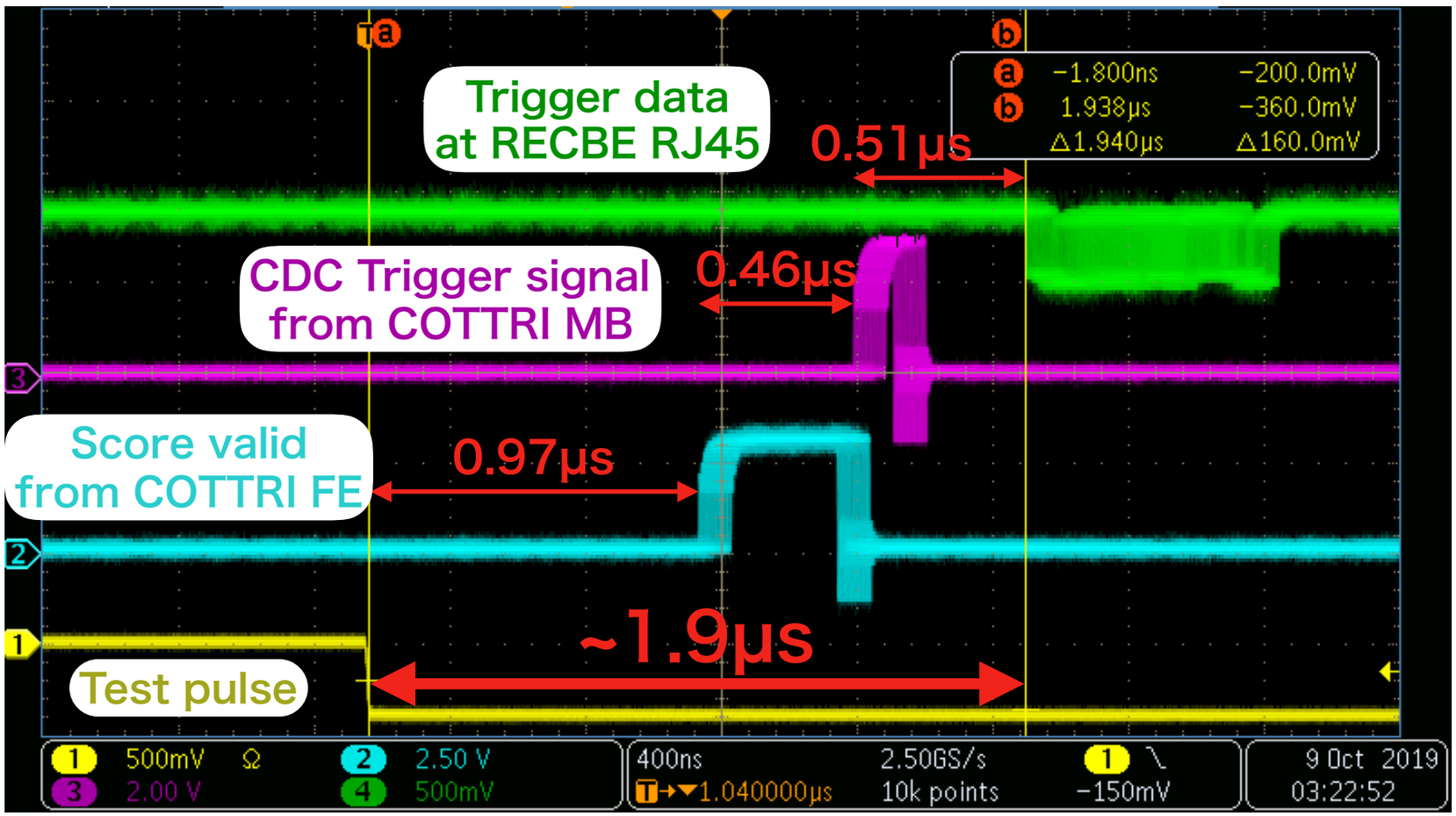
# Latency

**Requirement : <5 μs**

**Total : 3.1 - 3.2 μs**

| | Latency [μs] | Description |
|---|---|---|
| RECBE - COTTRI System - FC7 - RECBE | 1.9 - 2.0 | 100ns fluctuation by the data transfer rate of 10MHz |
| Drift time distribution | ~0.4 | Data evaluation every 100ns |
| Trigger receiving time in RECBE | 0.8 | 32bit trig. data with 40MHz |



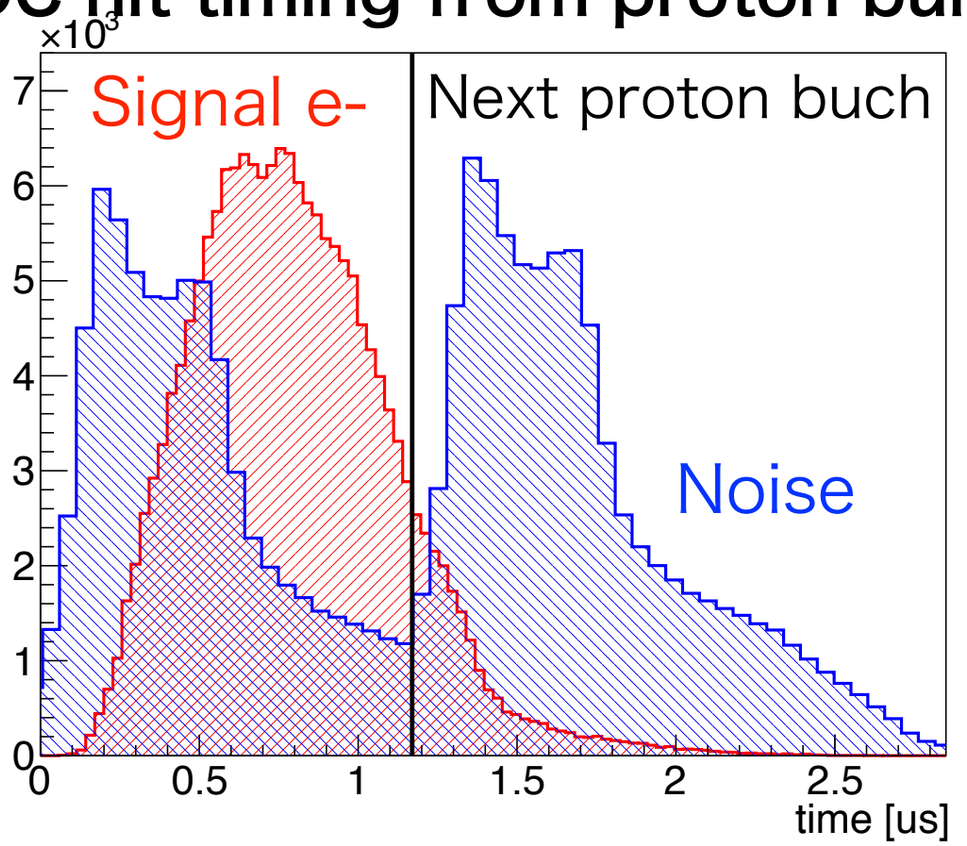
# Summary table of the processing time

| | | Latency [ns] | Description |
|---|---|---|---|
| RECBE | Digitization in the ADC chip | 268 | |
| | 10-bit ADC transmission | 33 | 10-bit ADC, 30MSPS |
| | 10-bit ADC to 2-bit data | 117 ?? | Receive and convert |
| | Data format | 125 ?? | ref. 2018 IEEE Proceedings |
| Data transmission from RECBE to COTTRI FE | | 308 ?? | 970 - (268+33+117+125+15+50+54) |
| 3m DP cable between RECBE and COTTRI FE | | 15 | |
| COTTRI FE | Error check & repair | 50 ?? | ref. 2018 IEEE Proceedings |
| | Integration within a time window | 400 | |
| | Score generation | 54 | |
| Data transmission from COTTRI FE to COTTRI MB | | 429 | Include data format and error check; 460 - (10+21) |
| 2m DP cable between COTTRI FE and MB | | 10 | |
| COTTRI MB | Trigger decision | 21 | |
| Data transmission from COTTRI MB to FC7 | | 125 - XXX ?? | 510 - (15+150+200+5+15) |
| 3m optical cable between COTTRI MB and FC7 | | 15 | |
| FC7 | Data processing | 150 ?? | ref. 2018 IEEE Proceedings |
| Data transmission from FC7 to FCT | | 200 ?? | ref. 2018 IEEE Proceedings |
| 1m optical cable between FC7 and FCT | | 5 | |
| FCT | Data processing | XXX | |
| 3m ethernet cable between FCT I/F and RECBE | | 15 | |
| RECBE | Trigger receiving time in RECBE | 800 | 32bit trig. data with 40MHz |

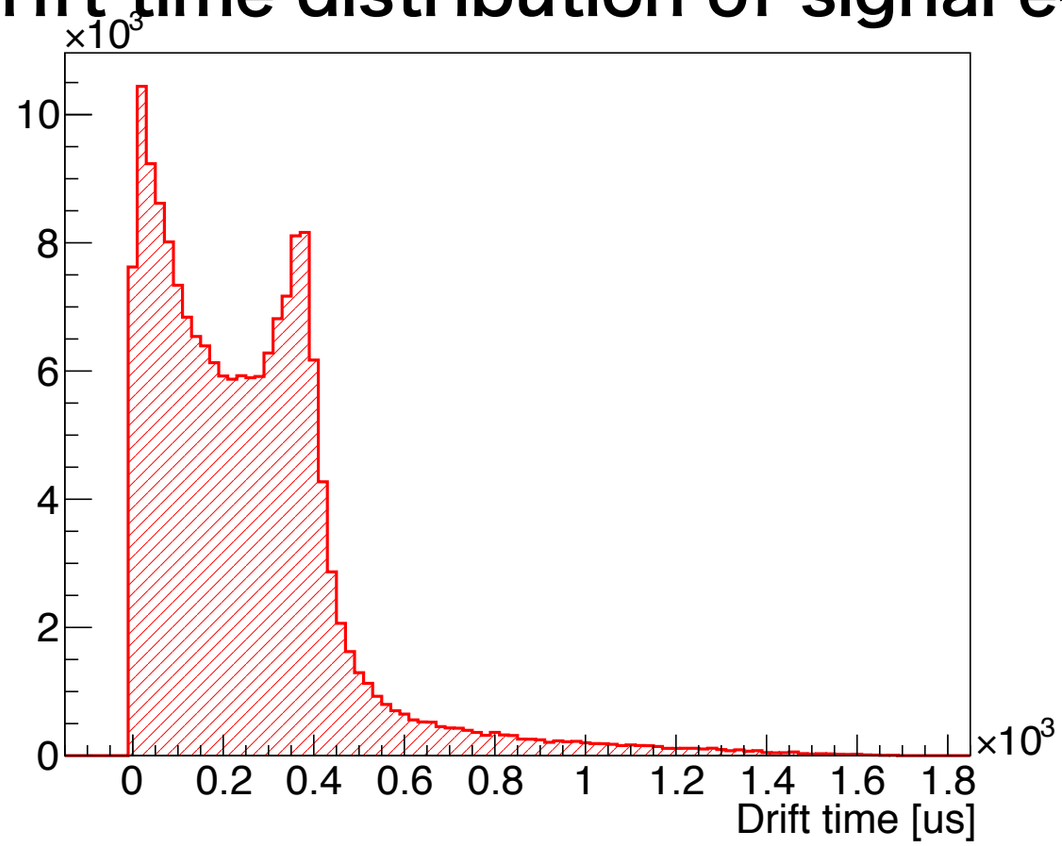
# Timing cut for trigger

- Measurement time window
  - Reduce noise hits related with beam background, muon decay in flight, and so on.
  - Candidates : 400 ns ~
- Trigger time window
  - Consider time width of drift time distribution in a cell.
  - Candidates : 300 ns, 400 ns, 500 ns

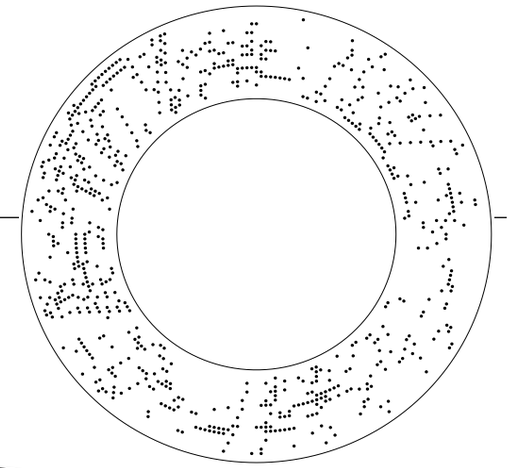
**CDC hit timing from proton bunch**



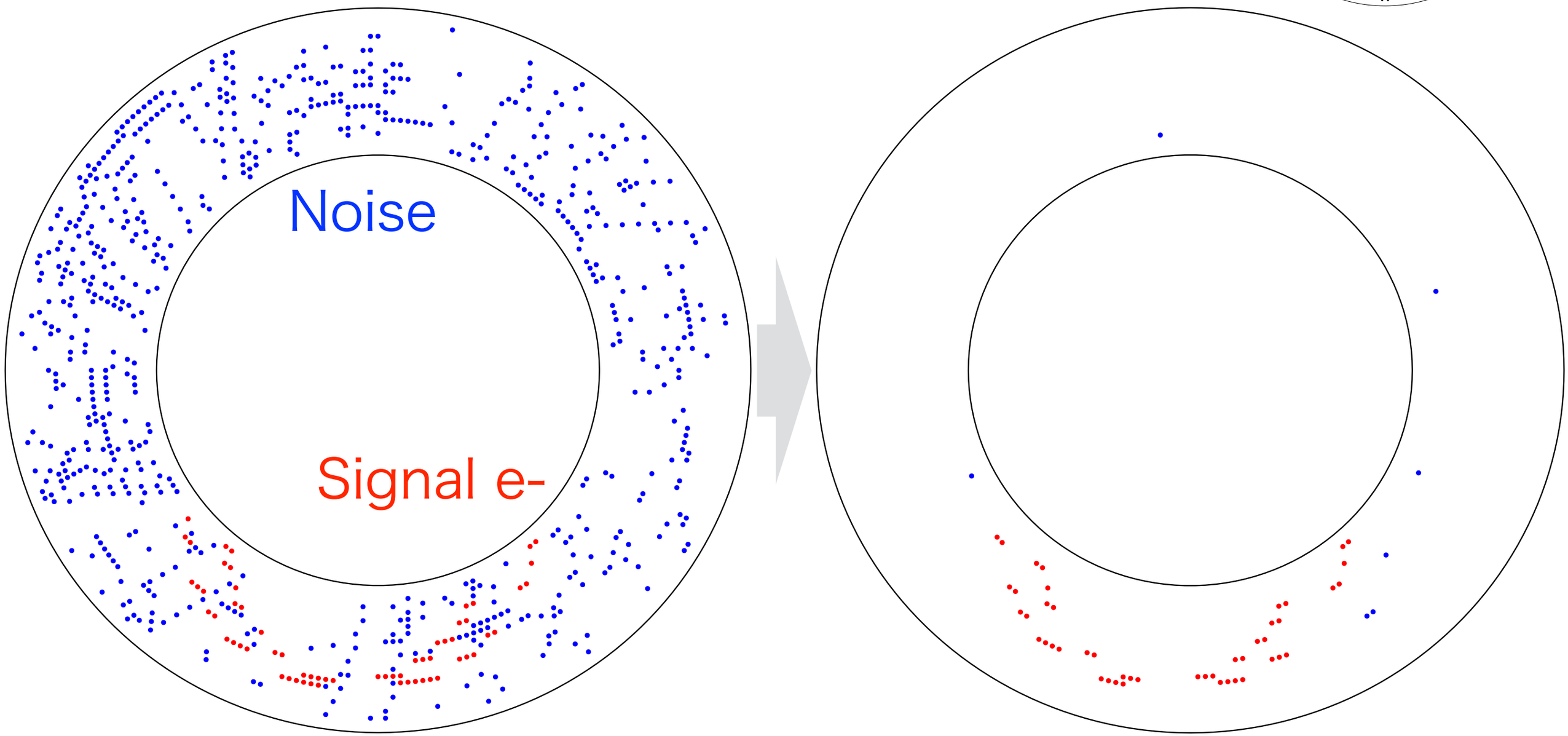

**Drift time distribution of signal e-**



# Hit classification



## Example

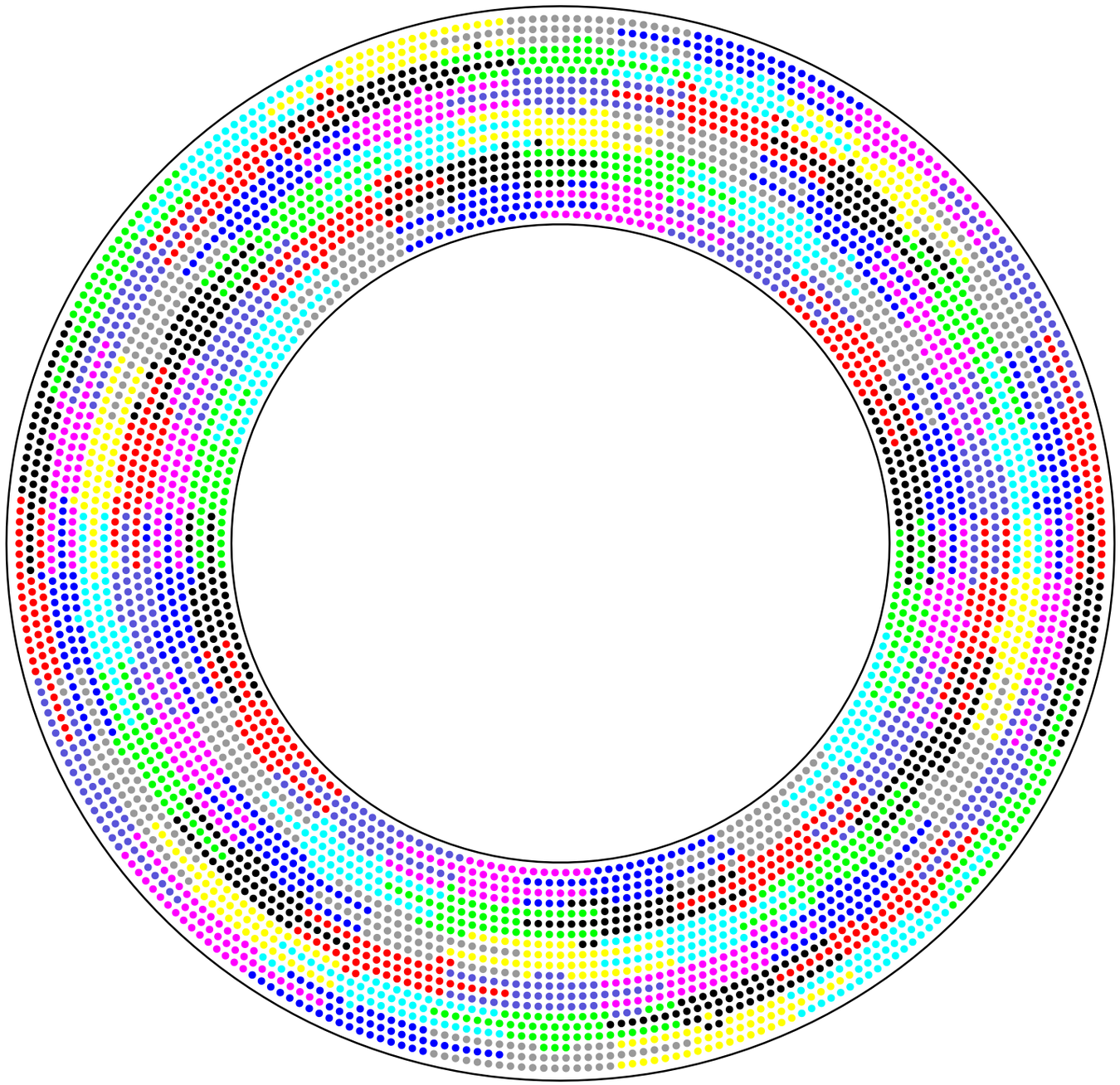



Discriminate hit using the threshold

(*) Stereo layers are used to provide info. about the third dimension of the hit location in CDC.

# Future work

## CDC Channel Map for RECBE



The channel map is decided by cable length between RECBE and CDC wire.

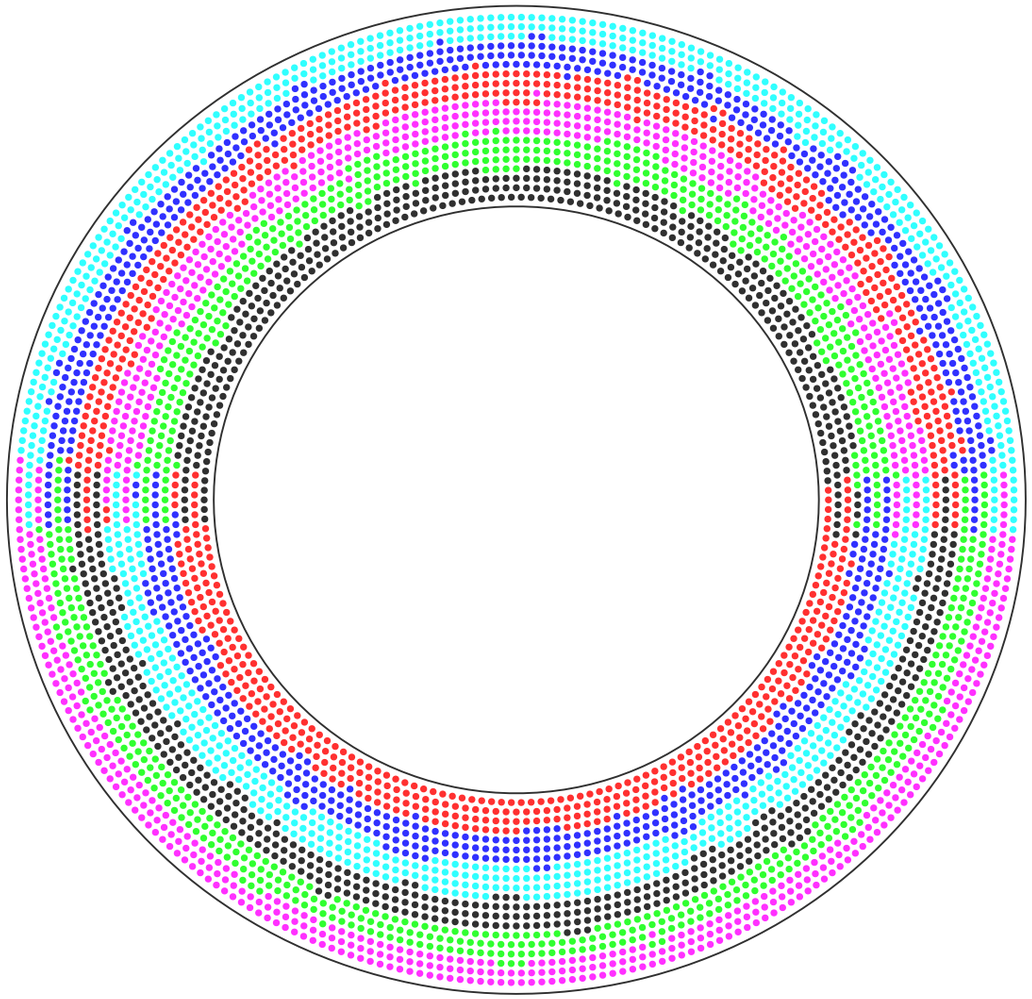
The cable length is as short as possible for noise reduction.

Therefore, this map seems very complicated and many points of discontinuous channeling are generated.

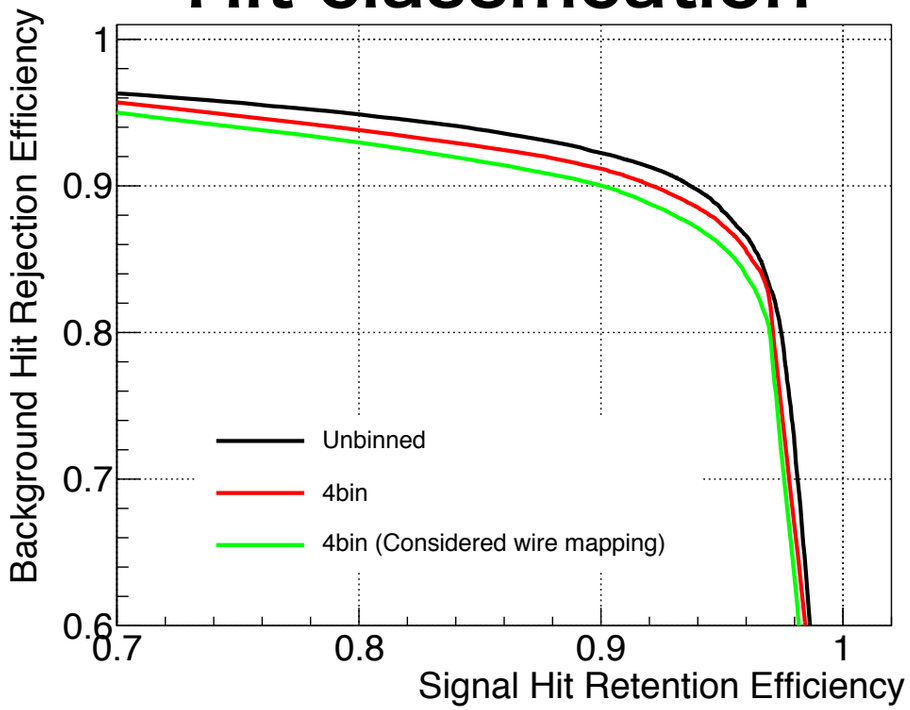
**What is the best assignment of RECBEs and COTTRI FE?**

# Future work

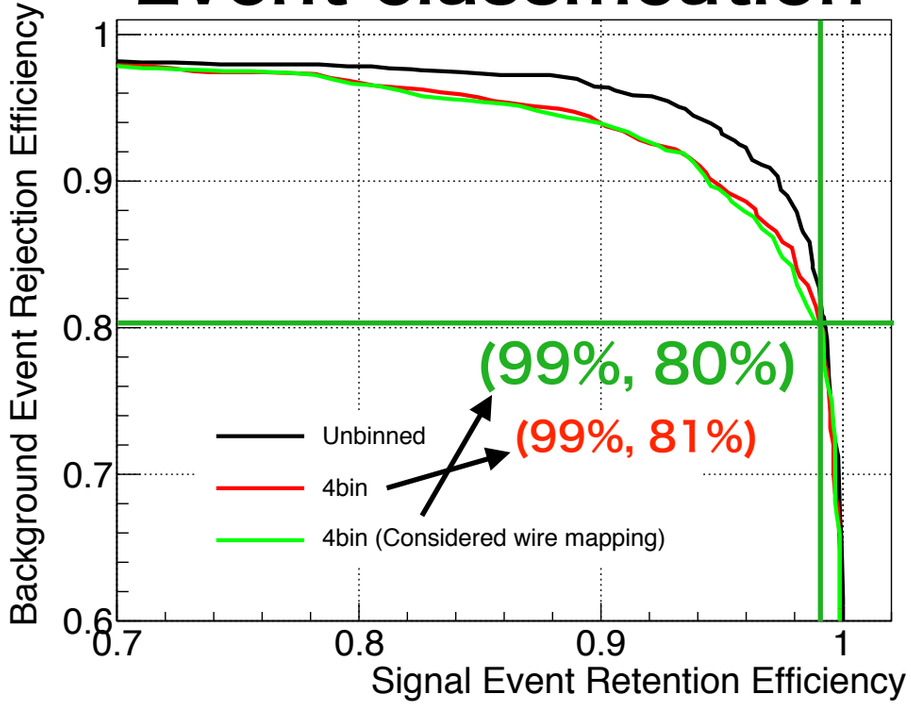
## CDC Channel Map for COTTRI FE



## Hit classification




## Event classification




This map is one of the worst case.

- Boarders of COTTRI FE coverages are close to the others.
- 2 COTTRI FEs in the outermost layer are not considered.

The result is quite better than I expected.

- Simulation data (~1500 events) is less statistics.