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

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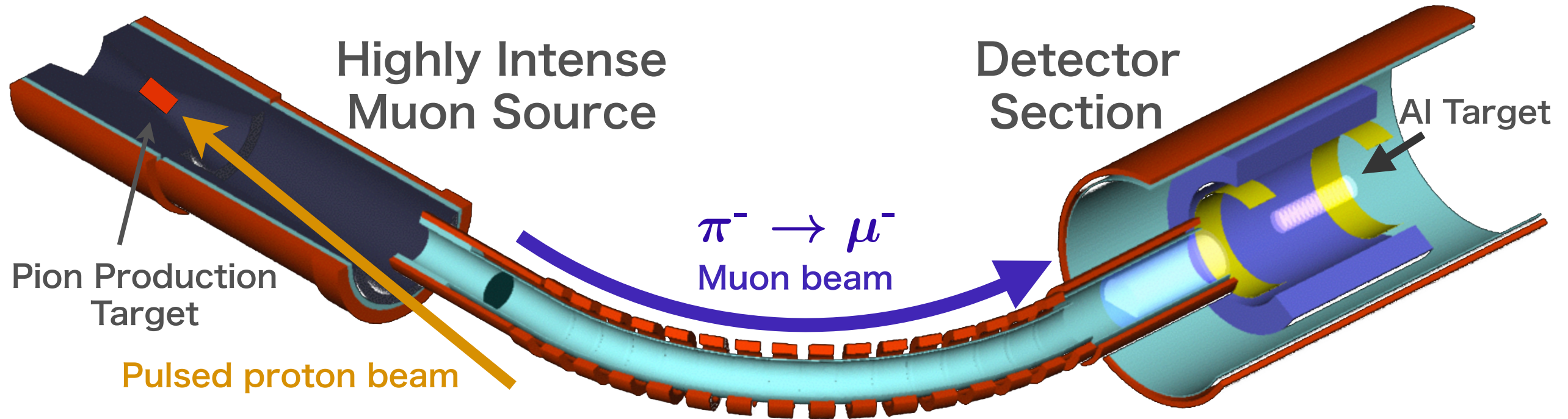
Y. Fujii, T.T. Chau, E. Gillies, M. Ikeno, M. Lee, S. Mihara, M. Shoji, T. Uchida, K. Ueno

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EPS-HEP Conference 2019 @Ghent



# COMET Phase-I @J-PARC, Japan



**Purpose :** Search for neutrino-less  $\mu$ -e conversion in Al

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

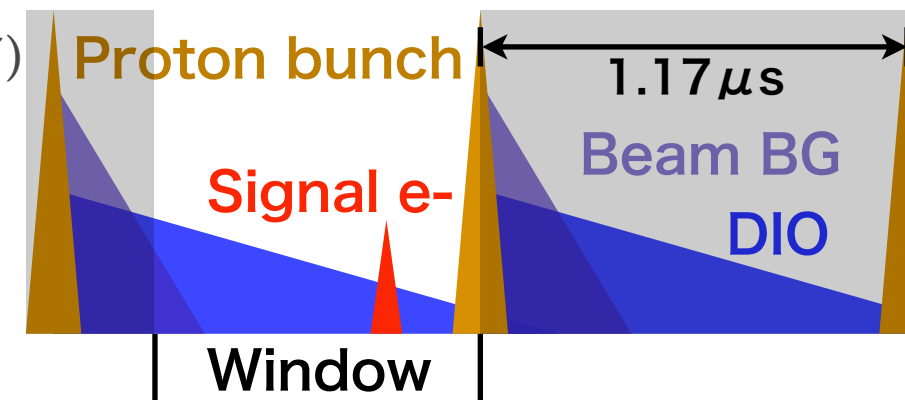
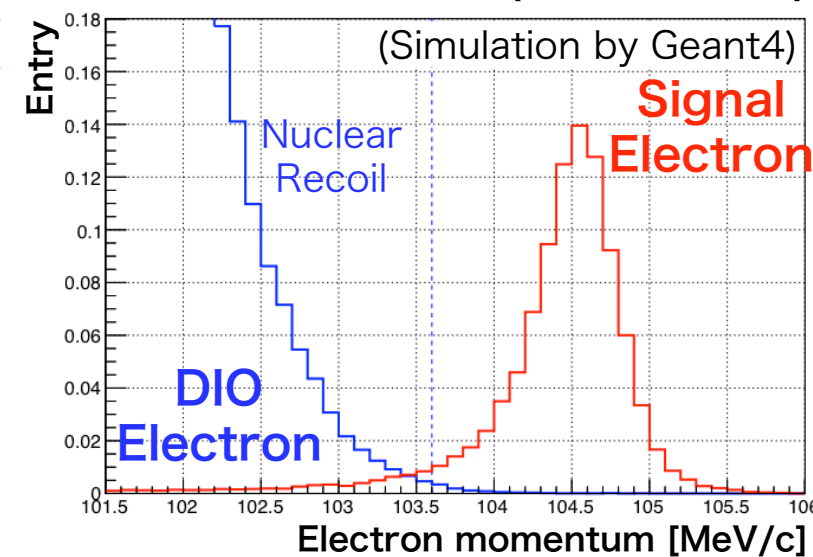
**Detector :** Cylindrical Detector System (CyDet)

**Signal :** 105-MeV single electron

**Background (BG)**

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

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



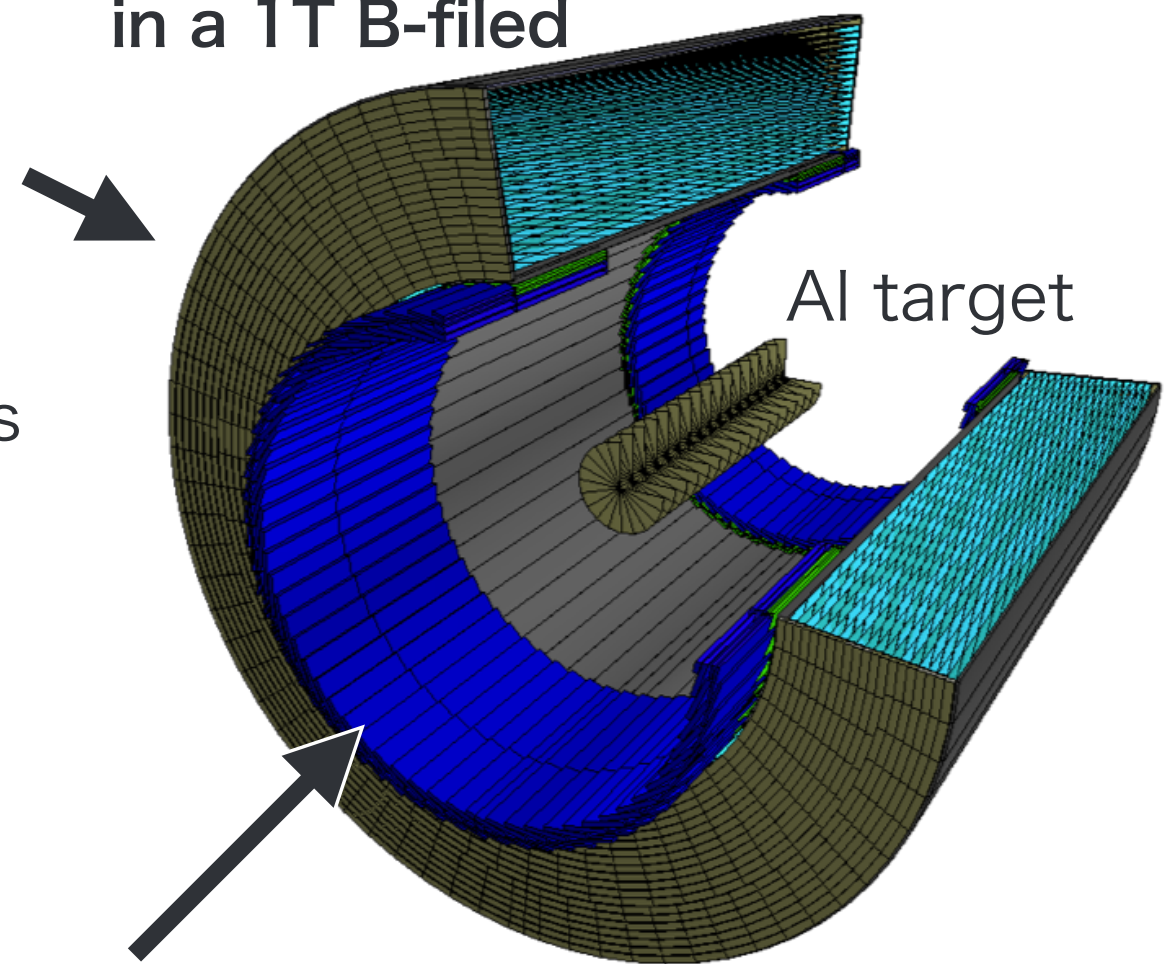


# Cylindrical Detector System

## 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

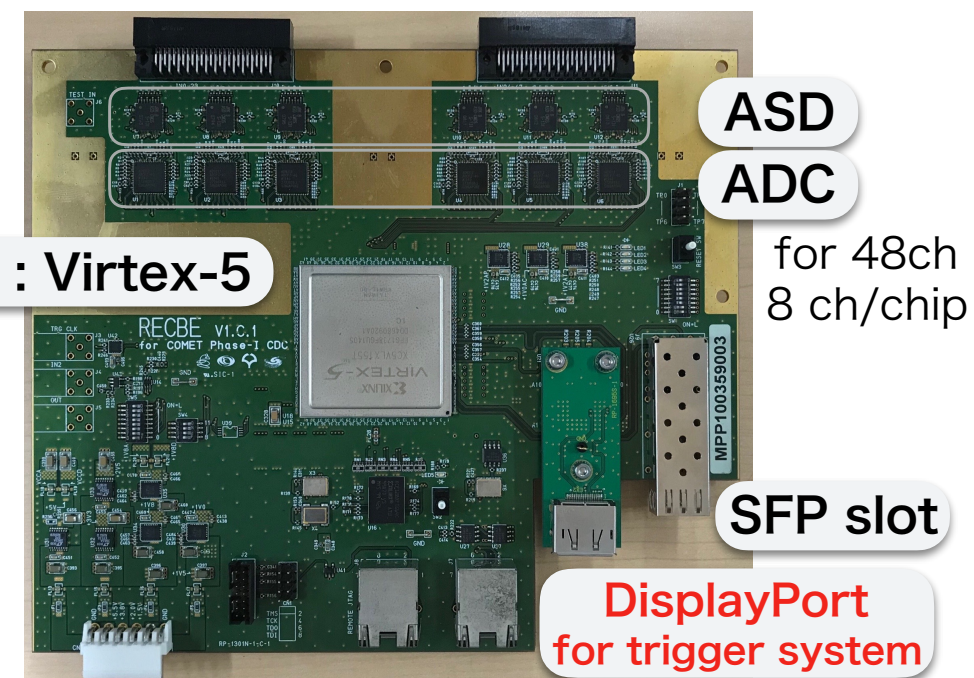
in a 1T B-field



## 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

**RECBE**



# Trigger requirement

Trigger rate :  $\ll 24$  kHz

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

Main constraint : Writing speed to storage

4-fold coincidence of CTH :  $\sim 27$  kHz

CDC Hit information : ??

**COTTRI System**  
(COfmet TRigger)

Latency :  $< 5$   $\mu$ s

Buffering time on RECBE : 8  $\mu$ s

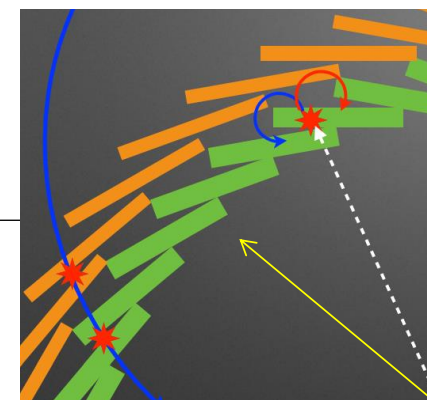
Event time window : 1  $\mu$ s

(+ 2  $\mu$ s Margin)

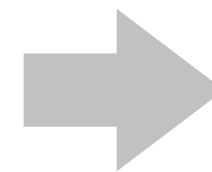
Efficiency : 99%

**Noise hit**

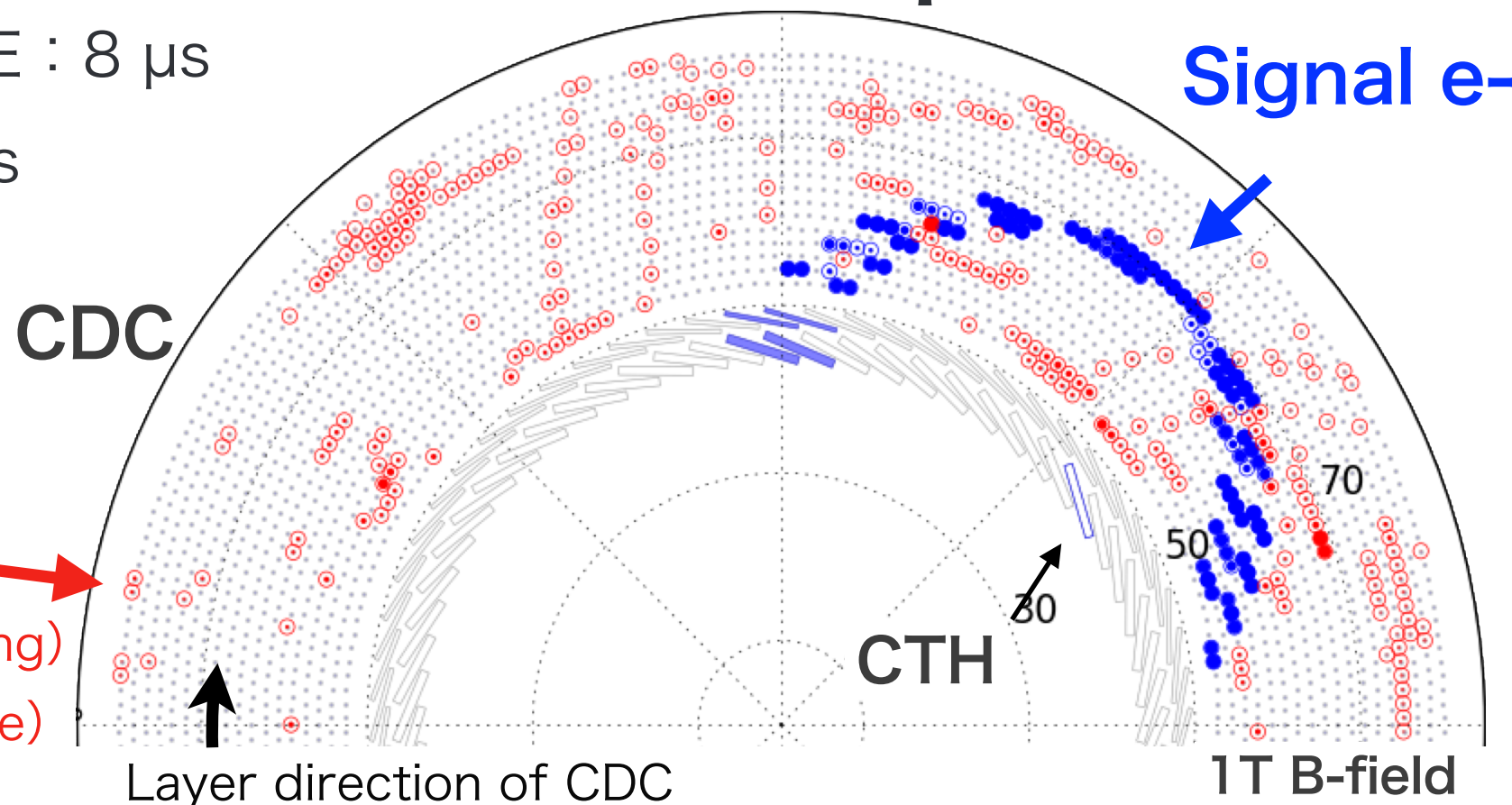
- $e^-$  (Pair-pro., Compton scattering)
- $e^+$  (Muon capture, Pion capture)
- Proton, and so on...



4-fold coincidence



## Hit map





# Online classification

## Gradient Boosted Decision Tree (GBDT)

TMVA in ROOT6

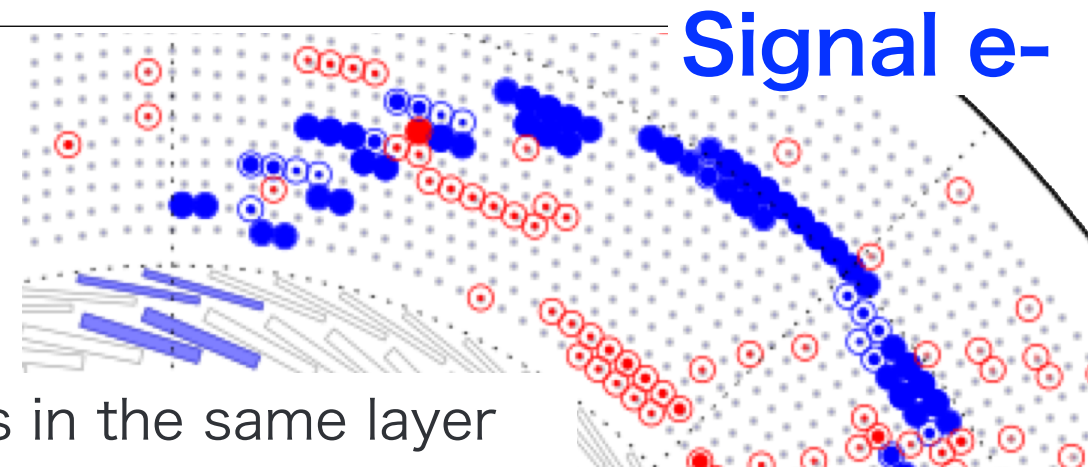
- Features

**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

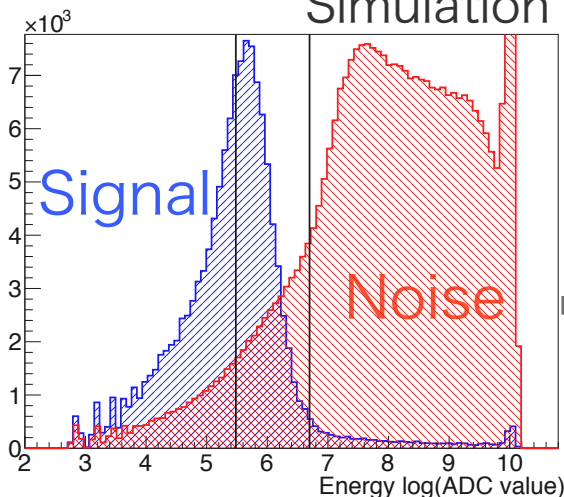
- The input-feature size is as small as possible due to the limitation from the data transfer rate for the online classification
- Look-up-tables inside a FPGA convert from the features to the GBDT outputs  
**within a clock cycle.**



## 2-bit Energy deposition CDC hit radial position

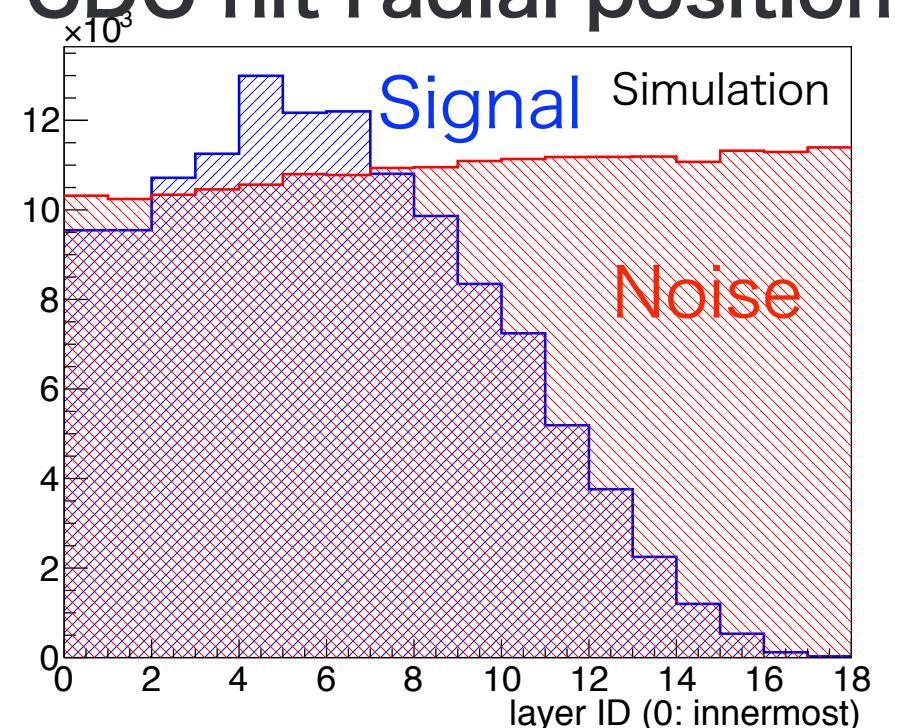
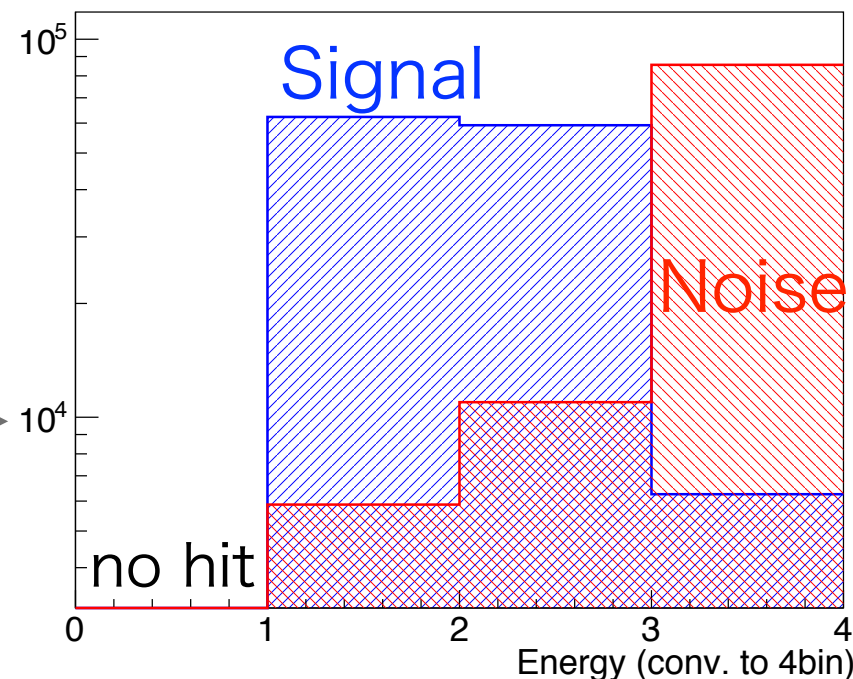
### Energy deposition

Simulation



3 bin  
+  
No-hit

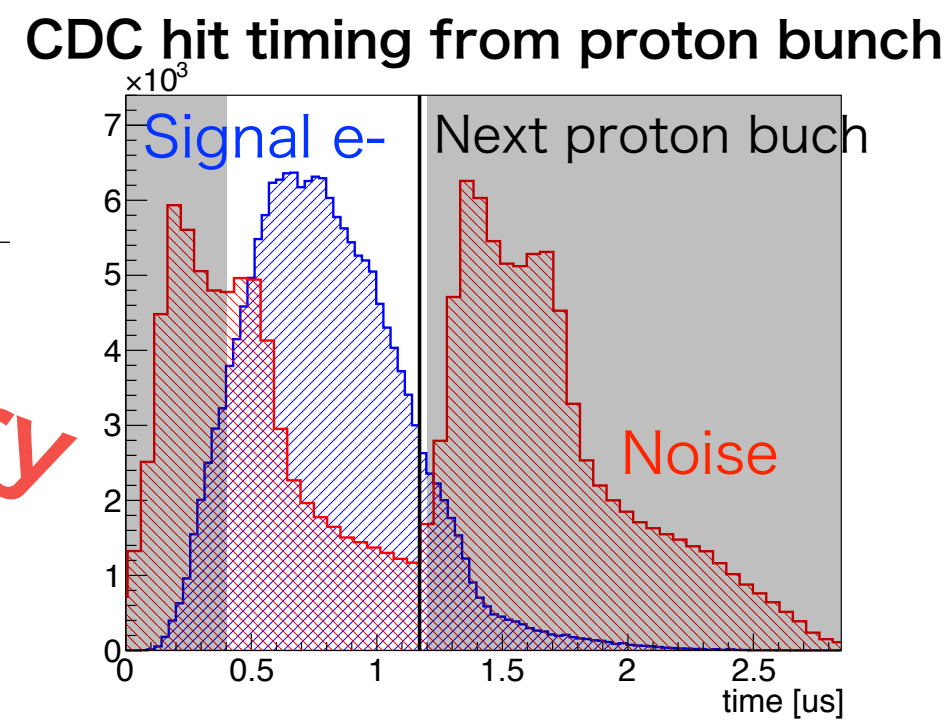
2-bit data



# Online classification

- **Trigger condition**

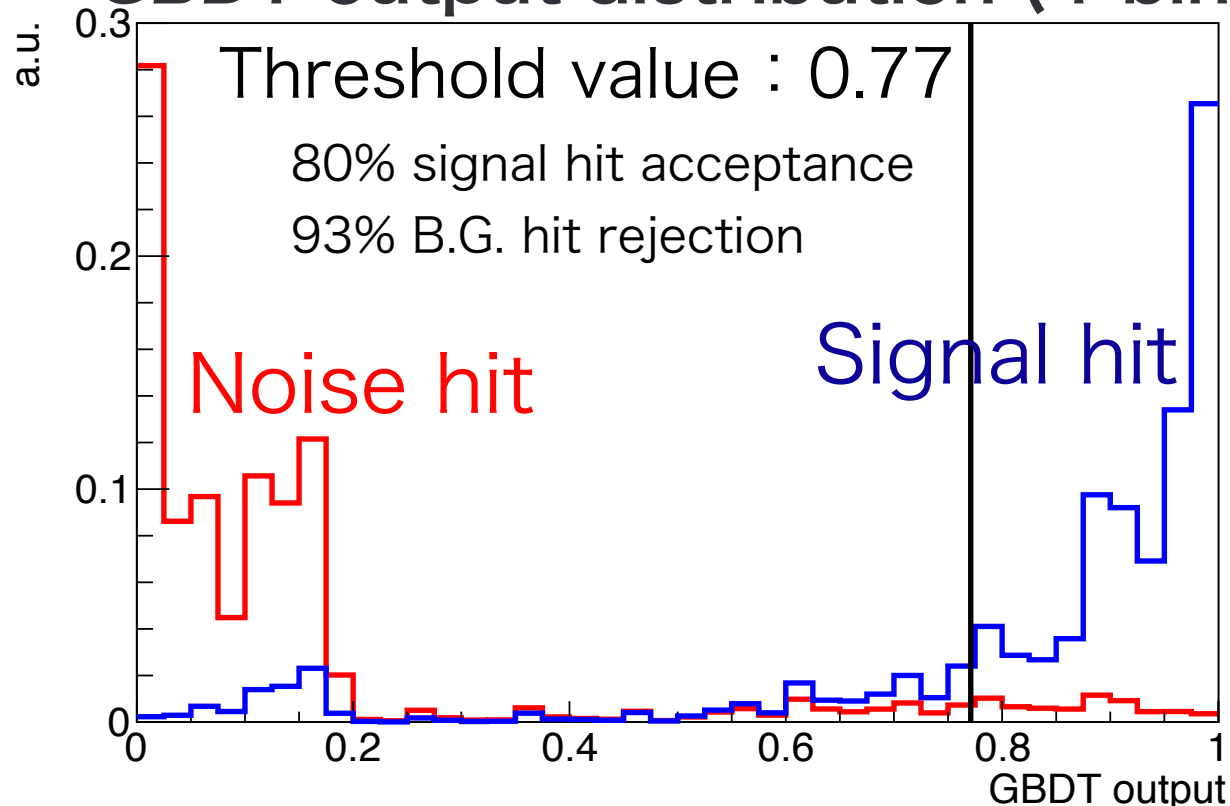
- Measurement-time window  
: 0.4 ~ 1.2  $\mu$ s from proton bunch
- Integration-time window : 400 ns
  - Consider the drift time in a CDC cell
- Sum up the GBDT outputs over threshold in the integration-time window
- Generate a trigger signal when the total GBDT output exceeds the threshold



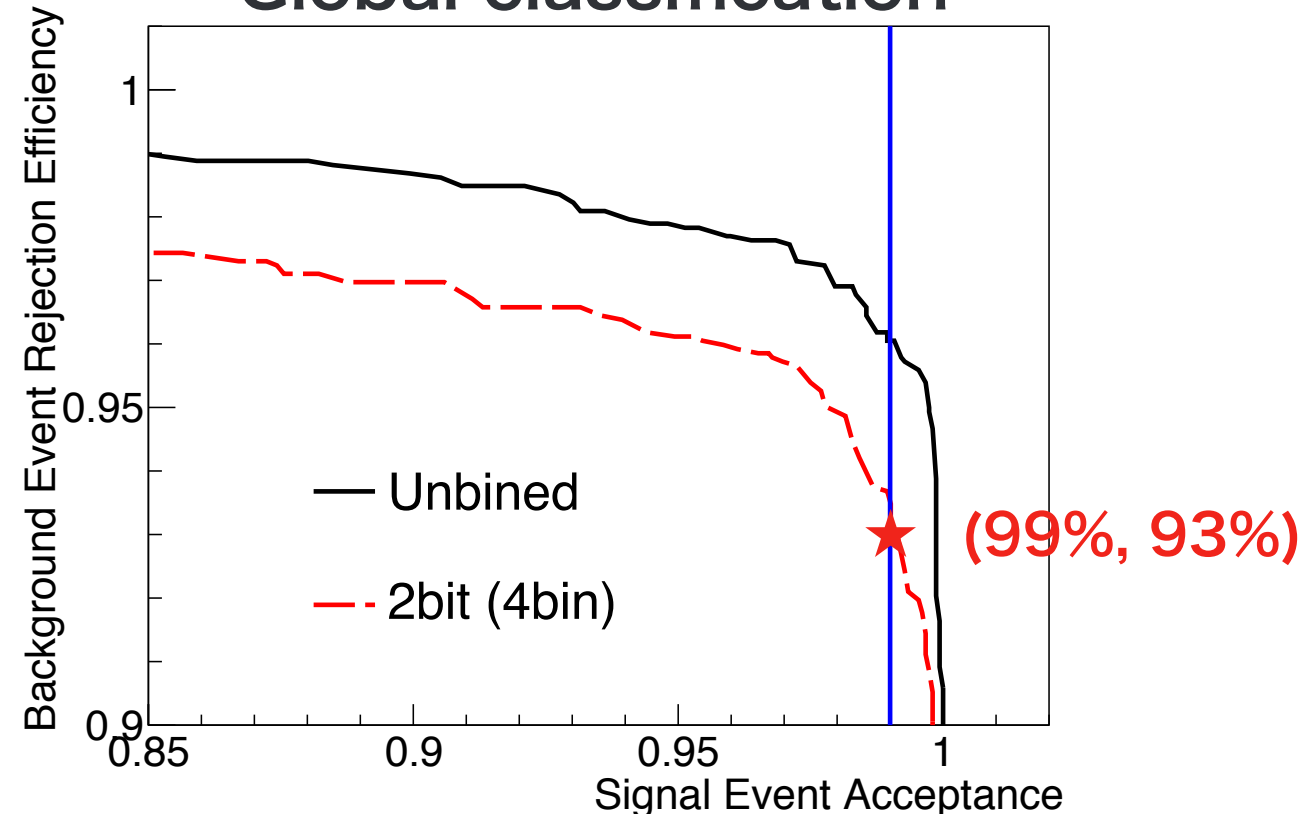
*Preliminary*

**Trigger rate ( $\ll 24$  kHz) :  $27 \text{ kHz} \times 7\% = 1.9 \text{ kHz}$**

## GBDT output distribution (4-bin)

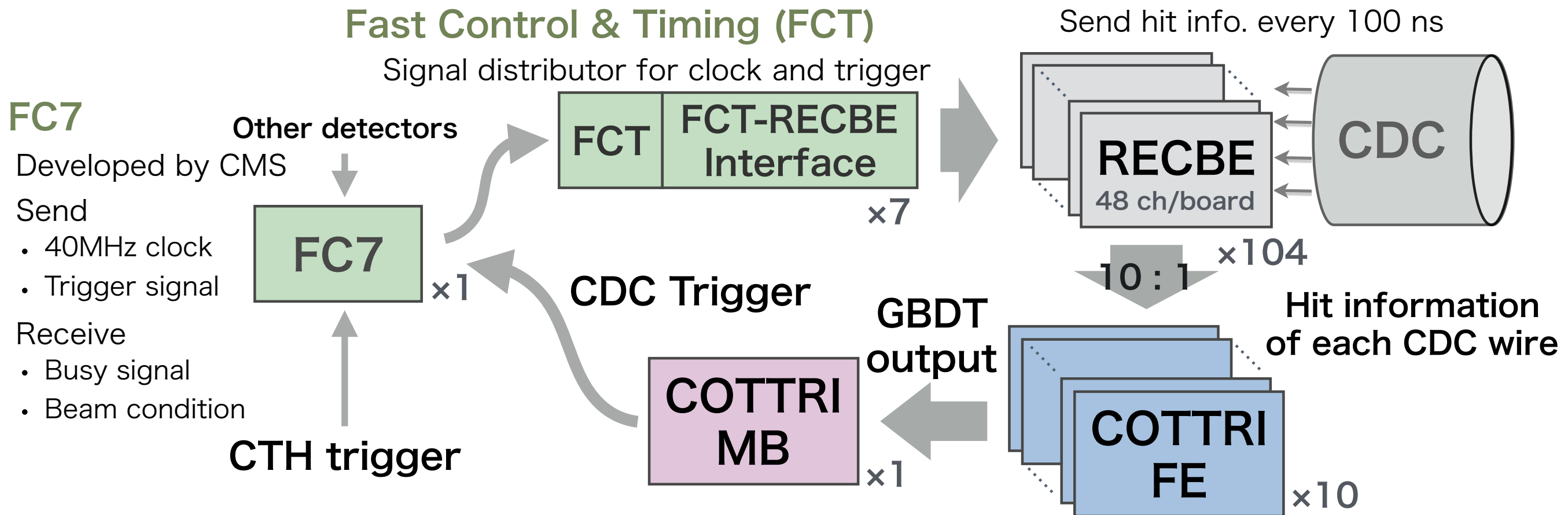


## Global classification





# 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 board

- The COTTRI prototype board was developed last summer.
- This board can work as both front-end and merger boards.

## 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

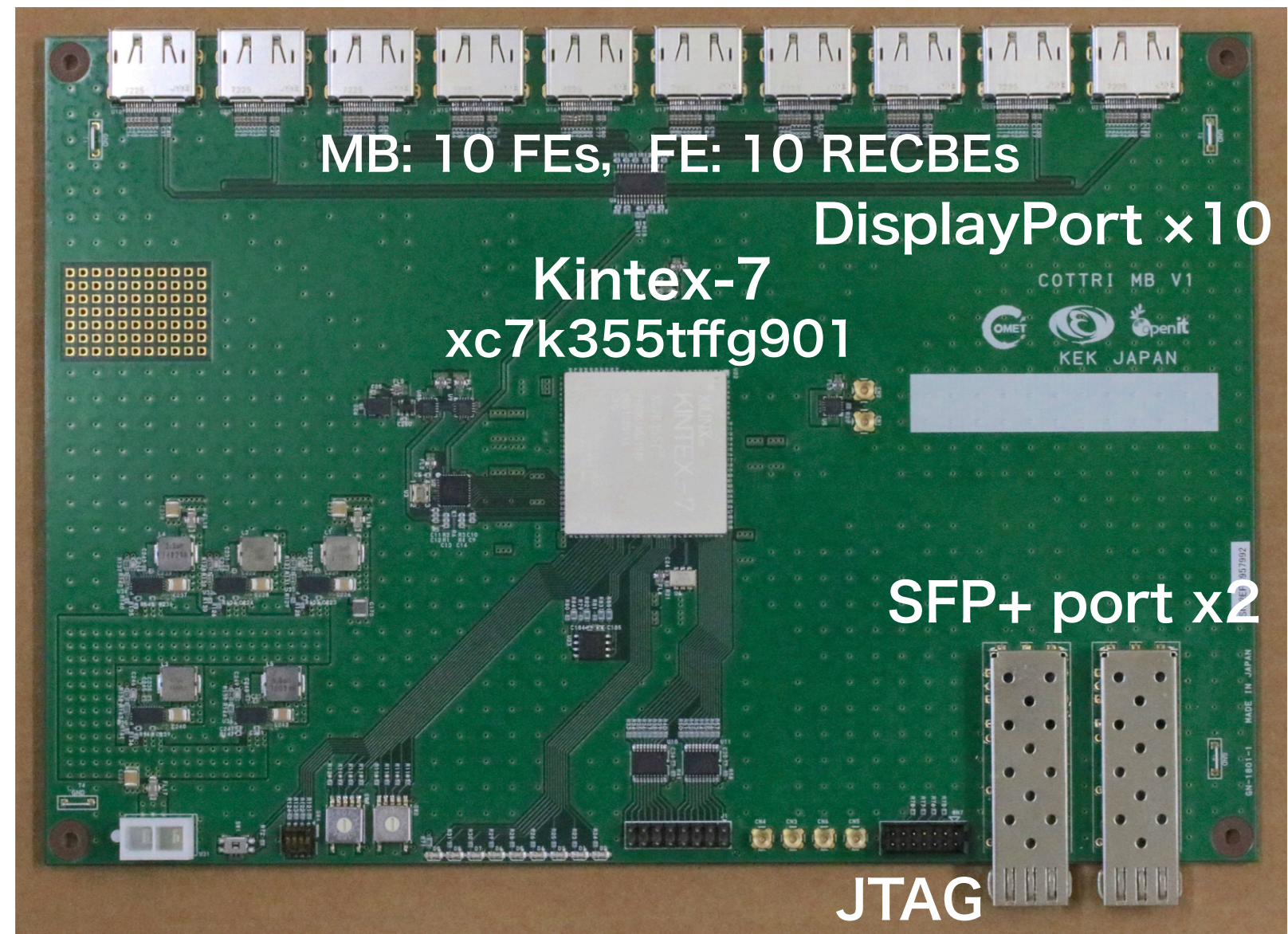
- Connect with GTX ports of FPGA

Max. data transfer rate : 5 Gbps/lane

## SFP+ port ×2

TX/RX : 1 lane ×2

For DAQ PC and FC7



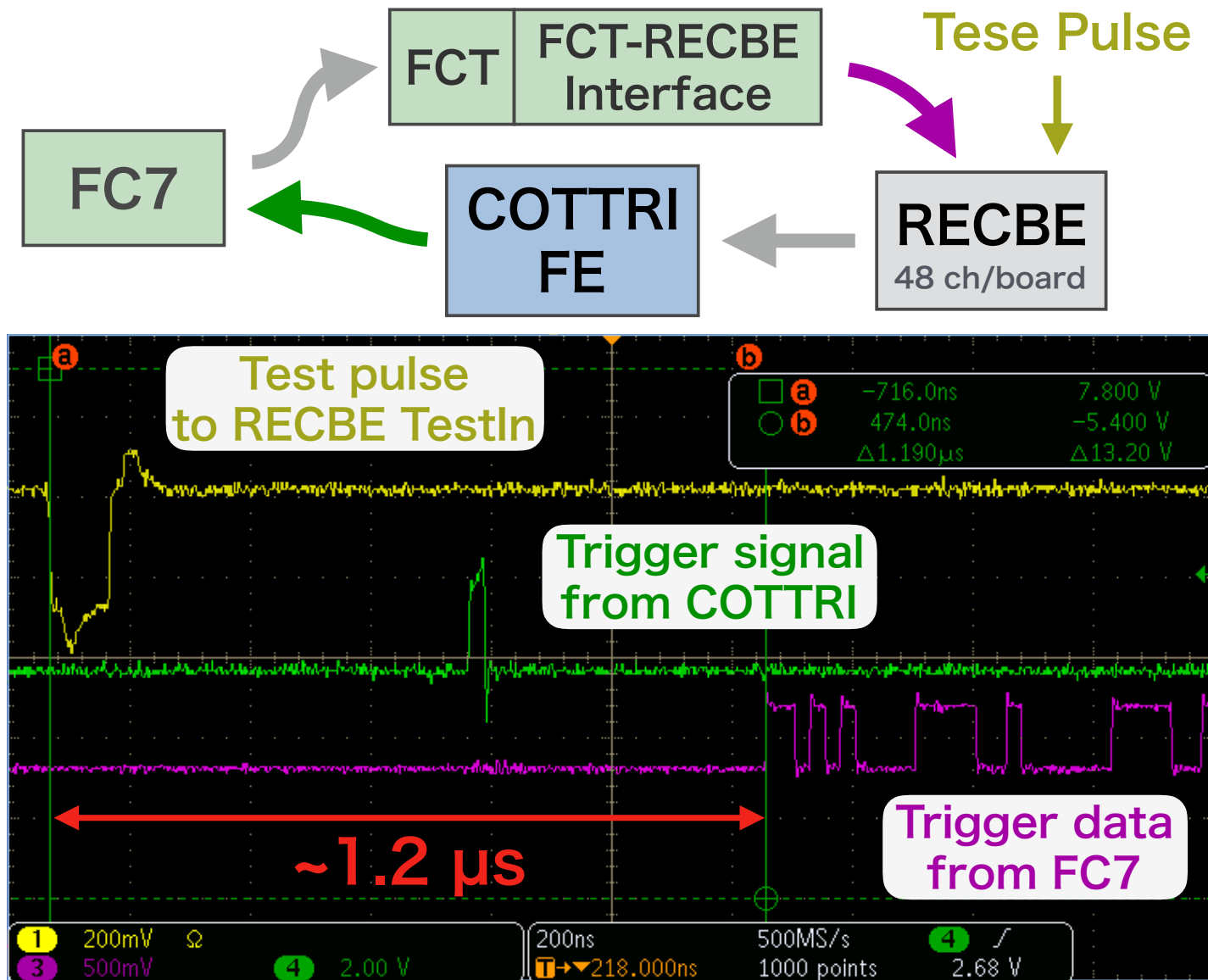


# Latency measurement

- RECBE - COTTRI communication
  - Aurora 8B/10B protocol
  - 120MHz GT reference clock
  - 3.84 Gbps/cable
- Measured latency: 1.2  $\mu$ s
  - RECBE - COTTRI FE - FC7 - FCT
  - Including the local/neighboring classification process

**Total expected latency  
2.8  $\mu$ s**

(Requirement: 5  $\mu$ s)

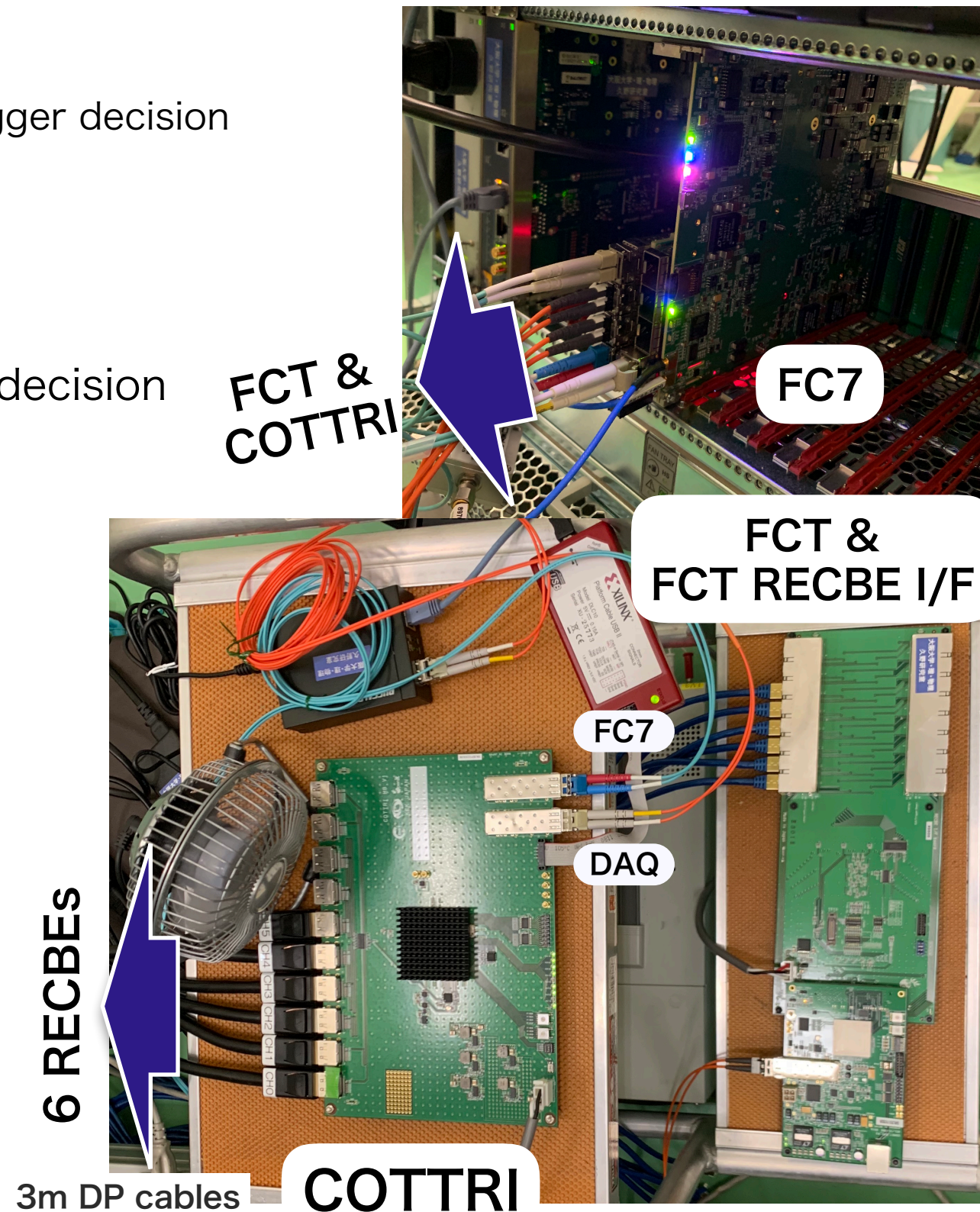
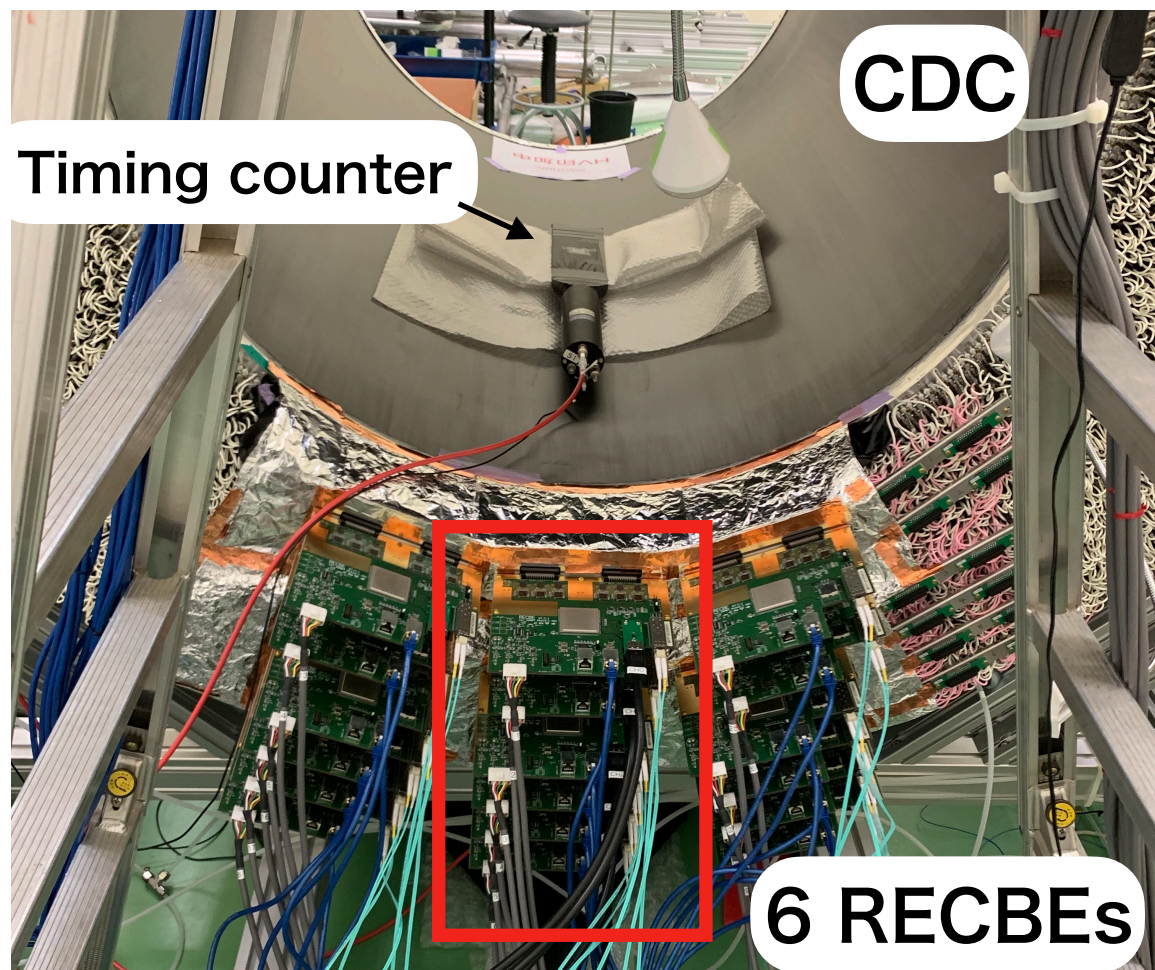


| Summary table for the latency                | Latency [ns] | Description                 |
|----------------------------------------------|--------------|-----------------------------|
| <b>RECBE - COTTRI FE - FC7 - FCT - RECBE</b> | <b>1190</b>  | <b>without COTTRI MB</b>    |
| <b>COTTRI MB</b>                             | ~400         | Similar process in FE       |
| <b>Drift time distribution</b>               | ~400         | Data evaluation every 100ns |
| <b>Trigger receiving time in RECBE</b>       | 800          | 32bit trig. data with 40MHz |



# Cosmic-ray test: Setup

- Trigger condition: CDC self-trigger or Timing counters
  - Use one COTTRI prototype board
  - Count the number of CDC hits and make the trigger decision using a threshold value in COTTRI
- Timing counter: Scintillators
  - locate both top and bottom sides of CDC
- The CDC-hit information used for the trigger decision was recorded from the COTTRI board.

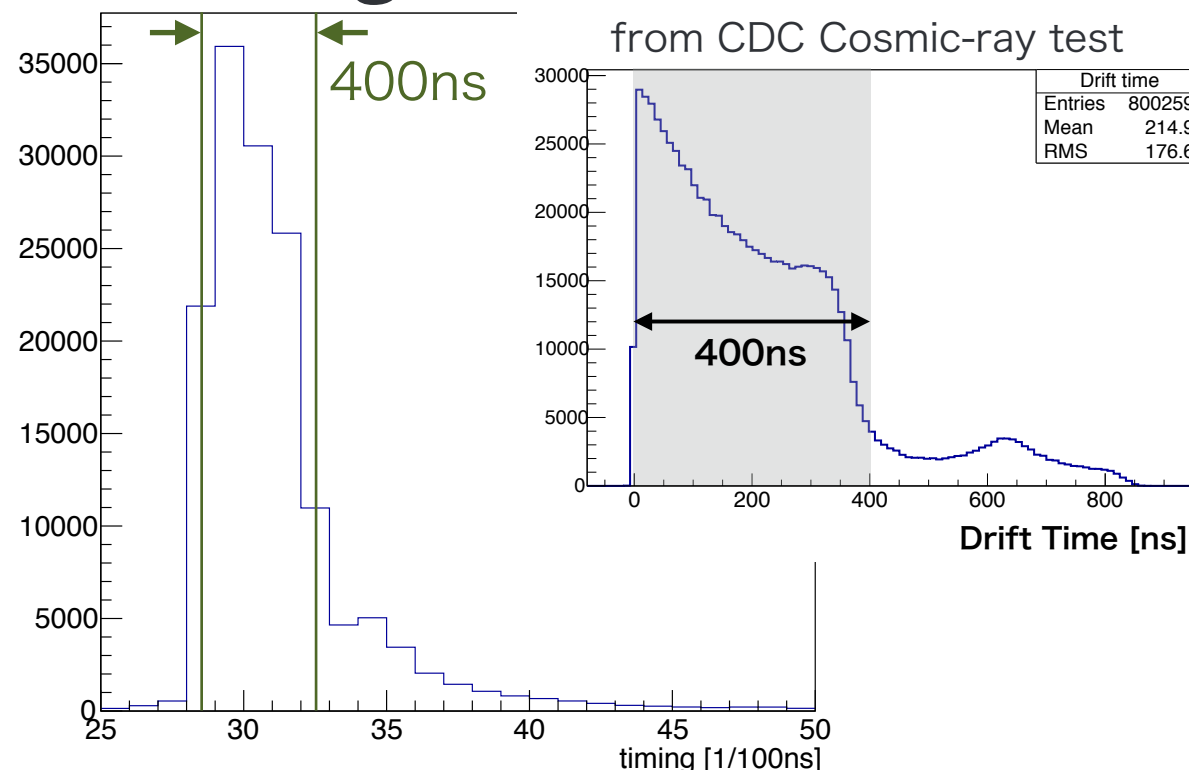




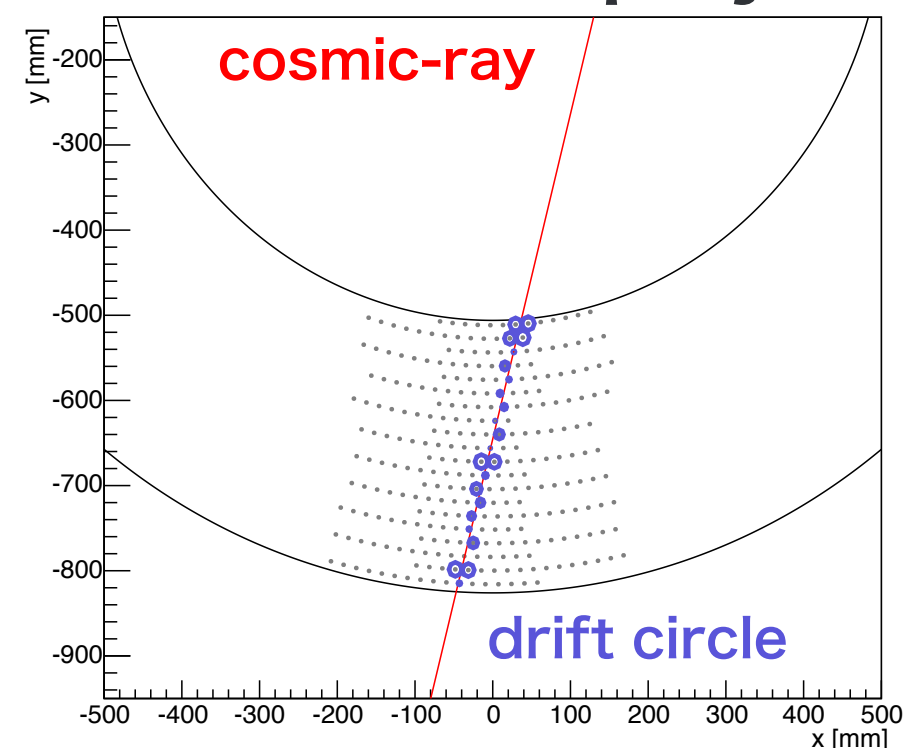
# Cosmic-ray test: Result

- 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.
- The online-trigger efficiency is at most 99.3% for the cosmic-ray events detected by the timing counters.
  - Including the inefficiency from the geometrical acceptance of the readout region

## Hit timing distribution



## Event display



# Summary & Prospects

- COMET Phase-I : Search for neutrino-less  $\mu$ -e conversion in Al
- **Trigger rate reduction is very important for the stable operation.**

Trigger rate : <24 kHz

Efficiency : 99%



## Online Classification Algorithm

- 99% signal acceptance with 93% background rejection efficiency  
→ Trigger rate : 1.9 kHz

Latency : <5  $\mu$ s



## Hardware development

- The COTTRI prototype board was already developed last summer.
- Total expected latency: ~2.8  $\mu$ s

- Data acquisition with using the COTTRI system in a part of the CDC setup was successfully done.
  - Cosmic-ray tracks were reconstructed.
  - The trigger efficiency of the system is more than 99%.

## Prospects

- Optimize the parameters such as the time window, the threshold values for the classification, and so on.
- Evaluate the COTTRI performance with a larger region of the CDC readout.

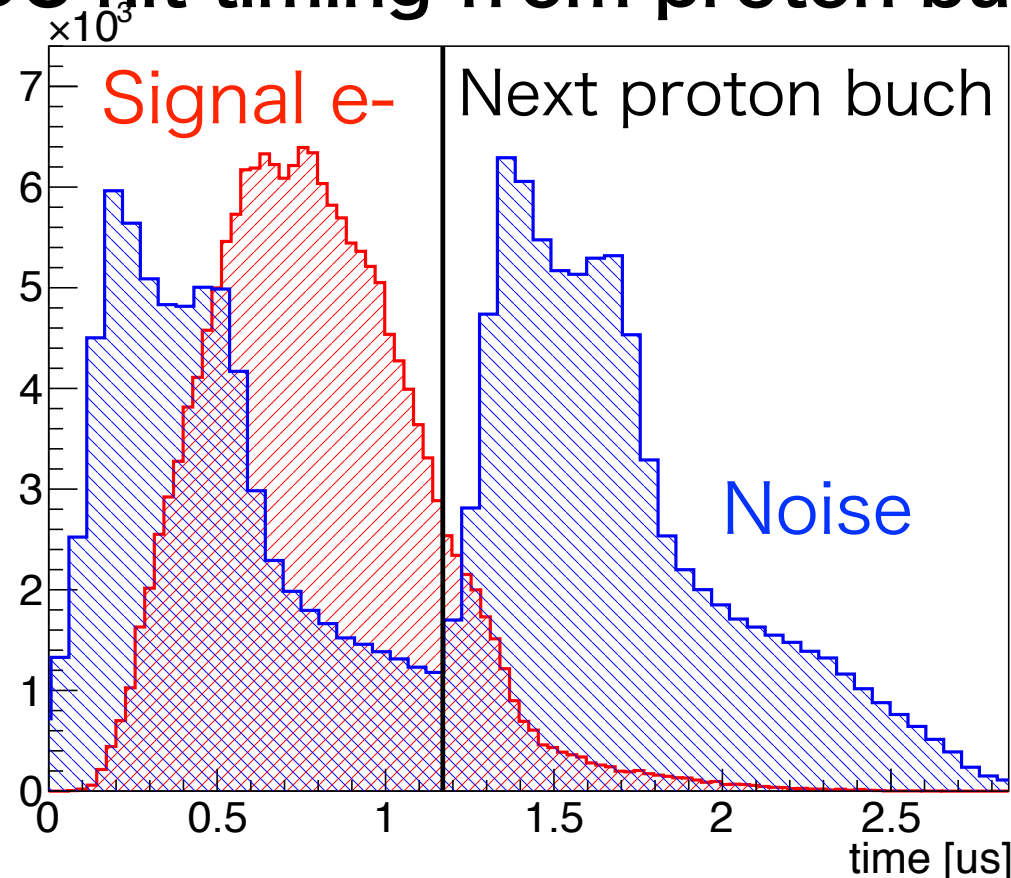


# Backup

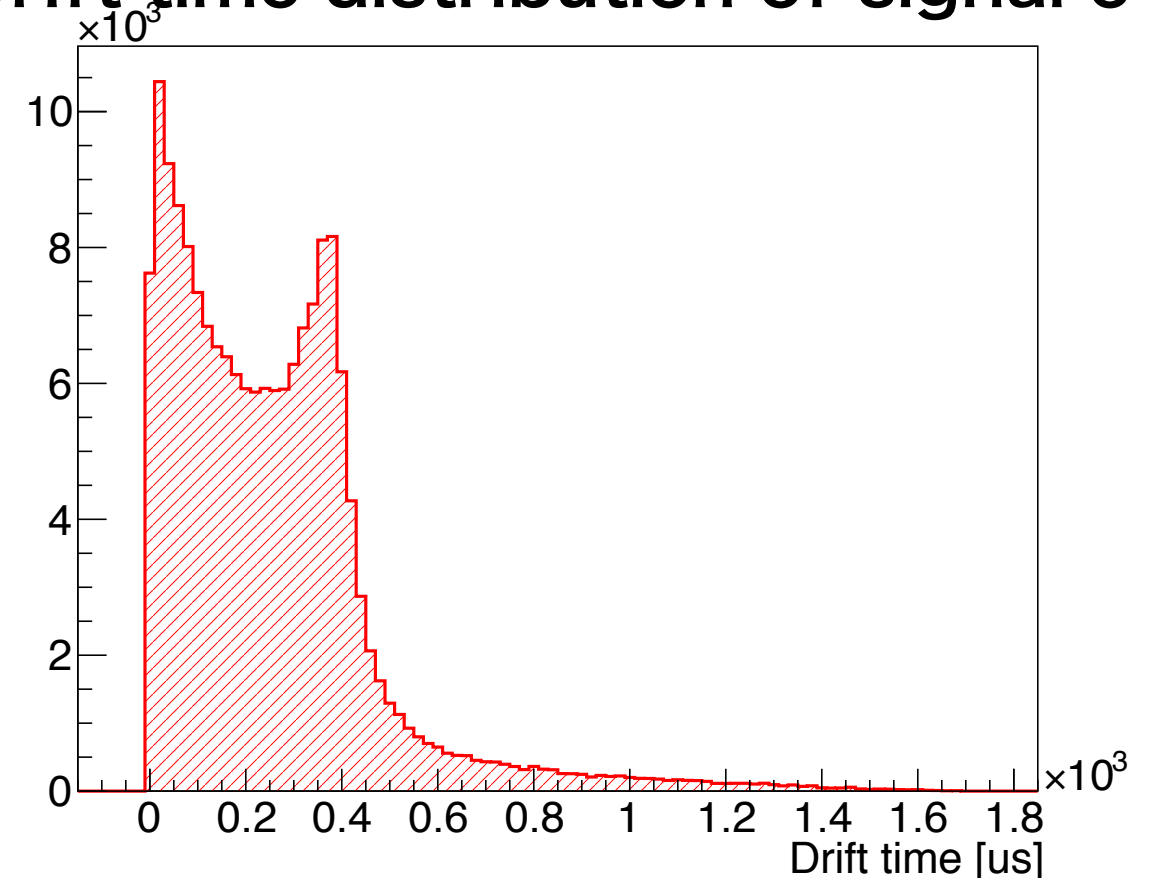
# Timing cut for trigger

- 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**



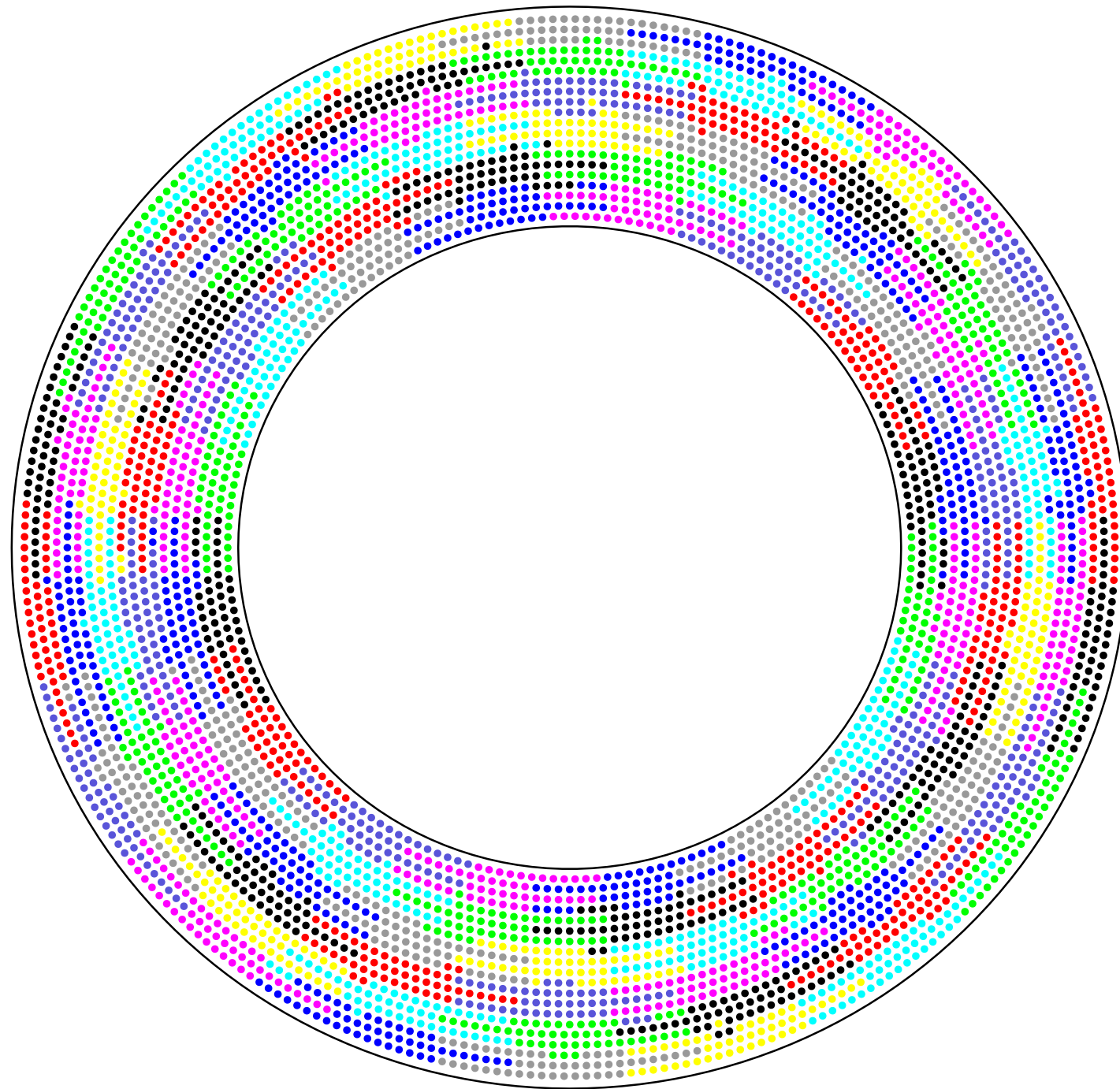
**Drift time distribution of signal e-**





# Future work

## CDC Channel Map for RECBE



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

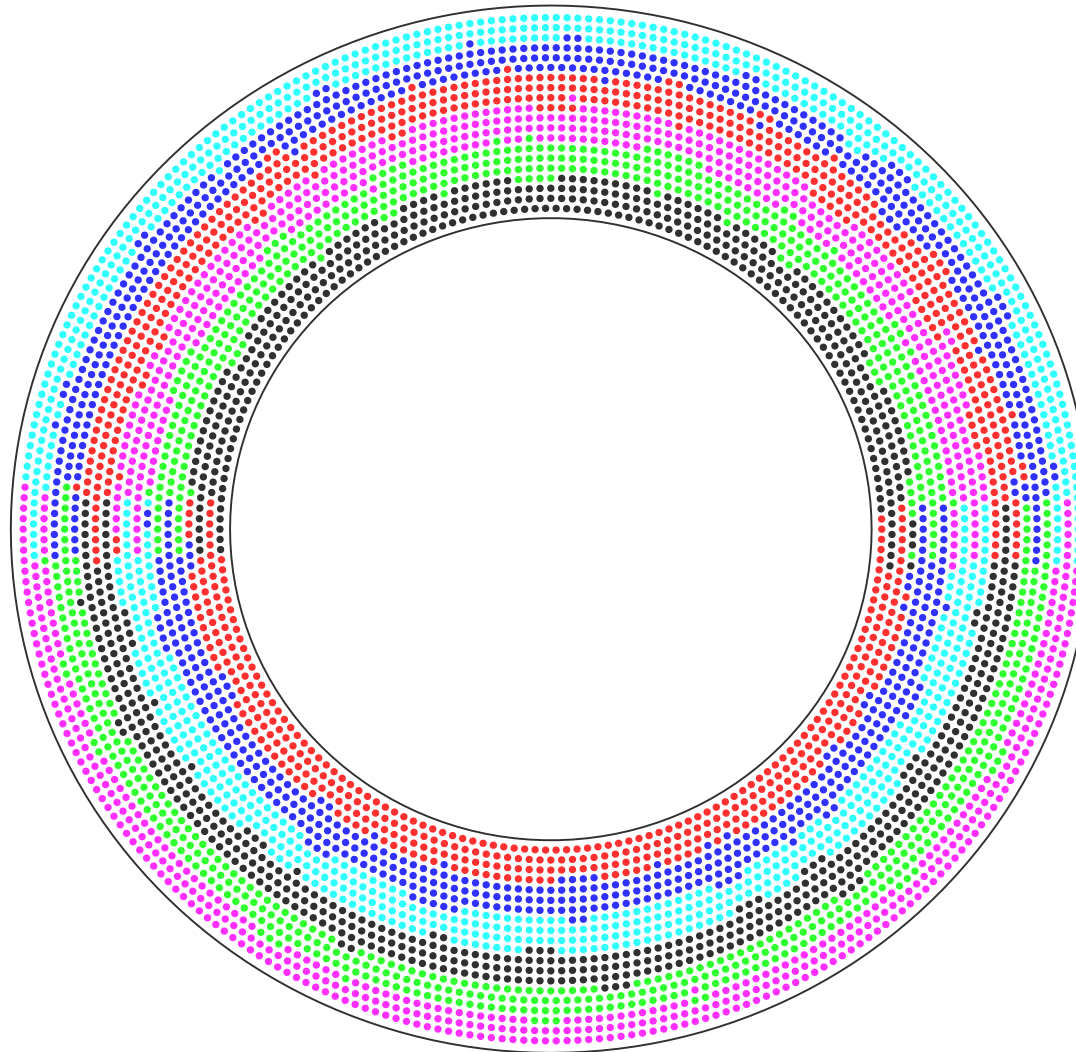
The cable length is as short as possible for noise reduction.

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 COTTTRI FE



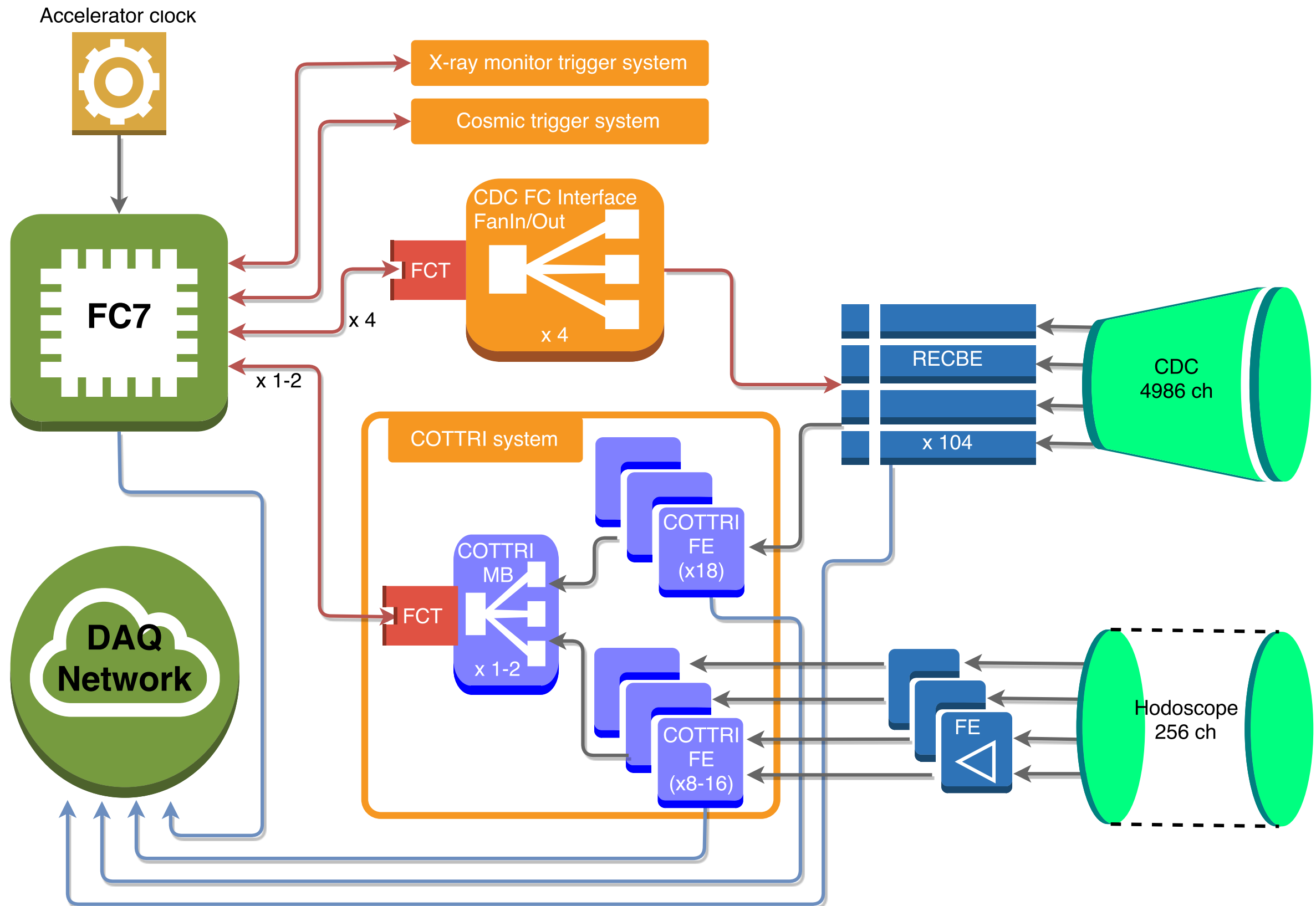
This map is one of the worst case.

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

The result is quite better than I expected.

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

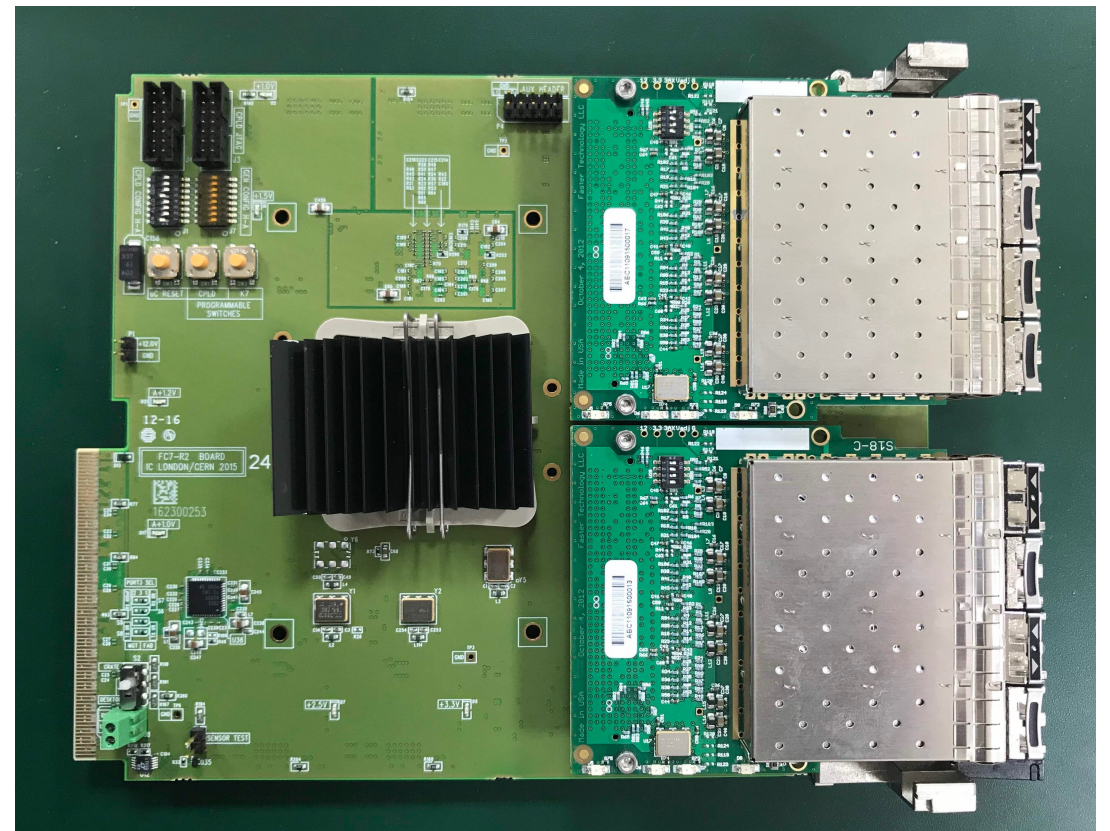
# COTTTRI System with CDC





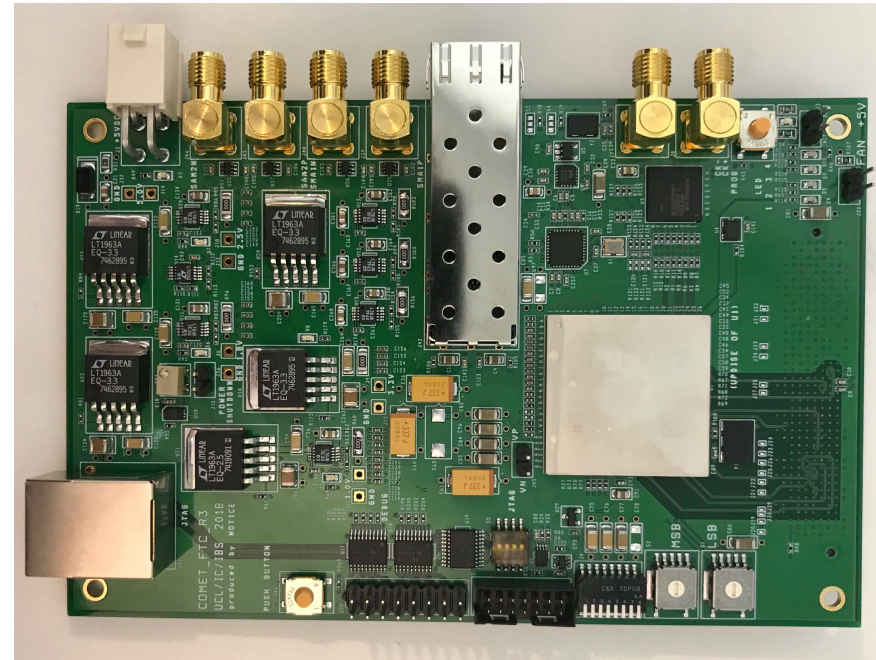
# FC7

- 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

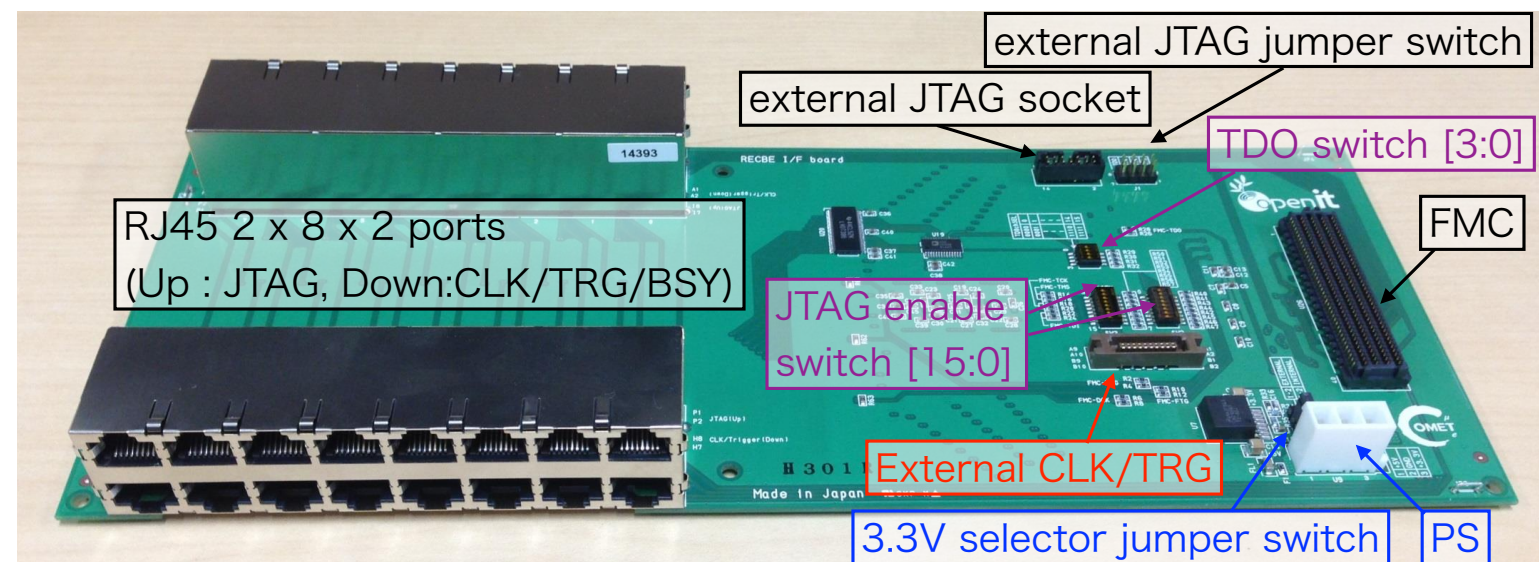
- Specification
  - Xilinx Kintex-7
  - FC7 MGT links
- Purpose



FCT

- Connection between FC7 and Front-end boards
- Fast control signal distribution
  - 40 MHz common clock
  - Trigger
- Firmware download
- Busy signal receiver

## FCT RECBE Interface



# Utilization of resources

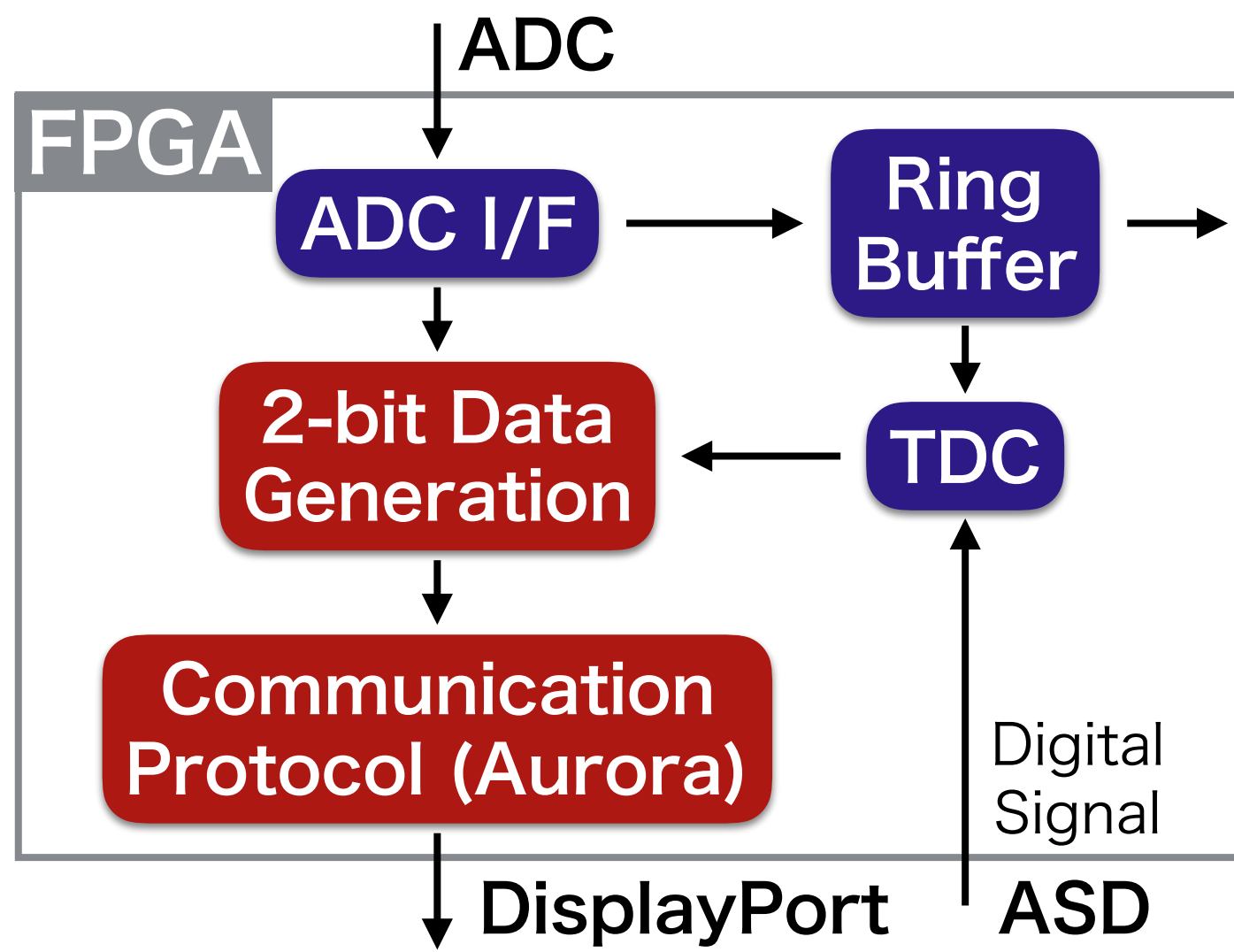
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| Resource | Utilization | Available | Utilization % |
|----------|-------------|-----------|---------------|
| LUT      | 5972        | 203800    | 2.93          |
| FF       | 13467       | 407600    | 3.30          |
| BRAM     | 15          | 445       | 3.37          |
| IO       | 11          | 500       | 2.20          |
| BUFG     | 3           | 32        | 9.38          |
| PLL      | 1           | 10        | 10.00         |



# 2-bit ADC data generation in RECBE

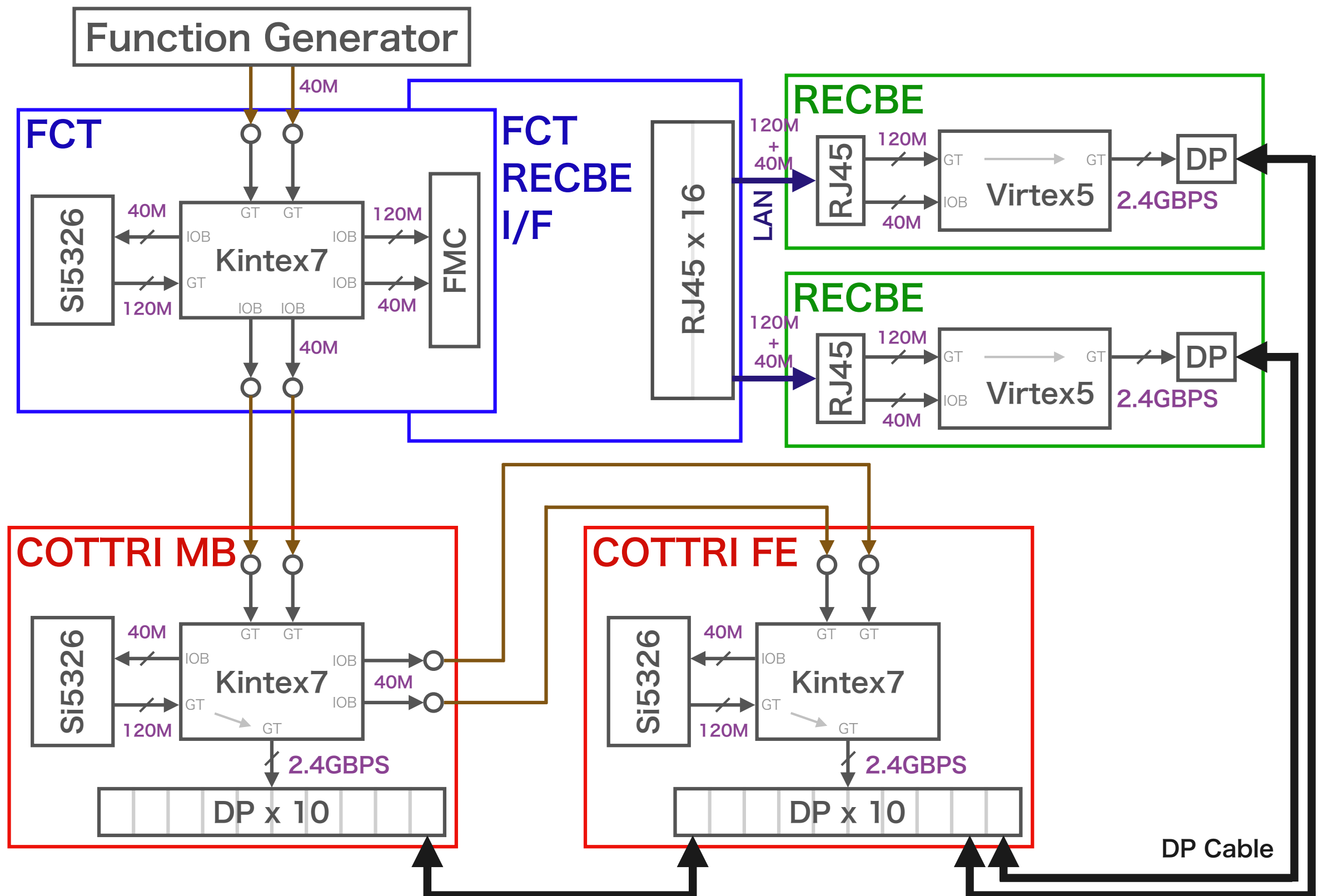
- Convert energy deposition to 2-bit
  - Sum up every 3 ADC samplings (every 100ns)
  - Without TDC hit, 2-bit data is “0”
  - Summed ADC is divided into 3 regions by using 2 thresholds. (“1”, “2” or “3”)
- Send 2-bit data to COTTRI FE
  - Aurora 8B/10B IP Core
  - 4.8 Gbps/lane w/ 120MHz GT clock
 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

# Current Setup (rough sketch)



# 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:  $<3.6 \times 10^{-15}$  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.



# COTTRI System

## COTTRI Front-end board

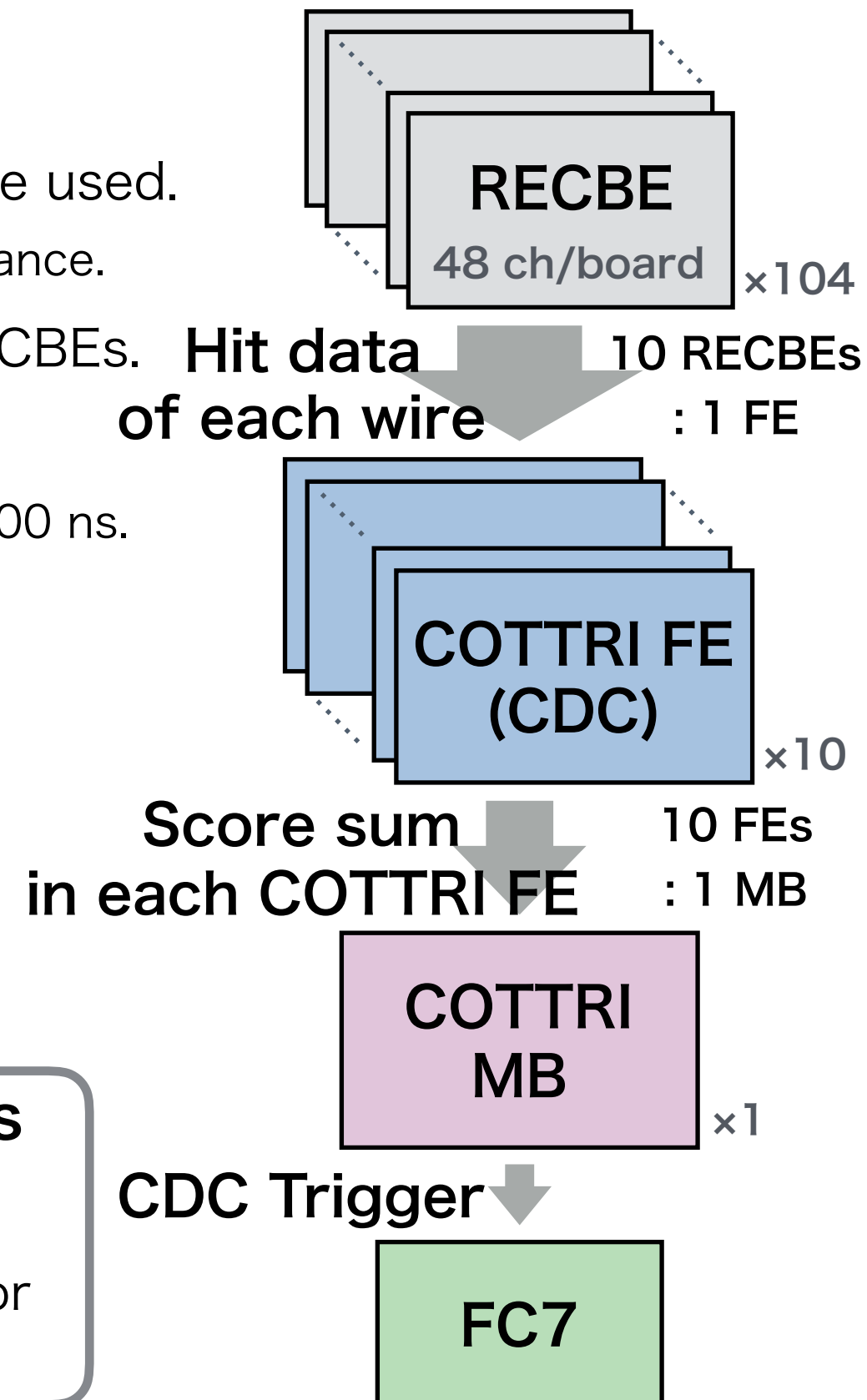
- 4 RECBs on the outermost layer of CDC will not be used.
  - They may have less contribution to the trigger performance.
- Receives 2 bit ADC data for 480 channels from RECBs.
- Gets scores from look-up tables.
  - 4 data points are used for the trigger time window of 400 ns.
  - $2 \times 3$  bit/ch (Left/Center/Right) is generated.
- Sends the score sum to COTTRI MB

## COTTRI Mother Board

- Sums up scores from all COTTRI FEs
- Decides trigger by using total score sum

**The COTTRI MB prototype can be used as the FE board for CDC.**

10 DisplayPorts for RECBs and 2 more GTX lanes for COTTRI MB.



# Test firmware

