COMET実験における計測システムの現状と将来に向けた新規開発

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計測システム研究会2021@九州

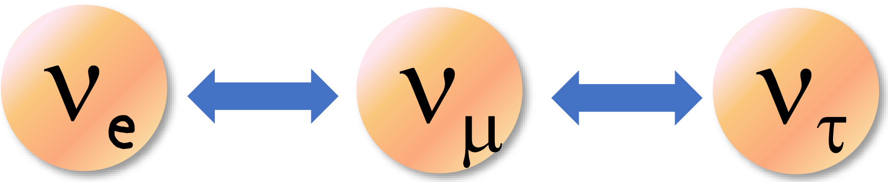
Outline

- Introduction
- COMET experiment
  - COMET detector system
  - Issues
- Radiation studies
- Toward the future experiment
  - NanoBridge FPGA
- Summary

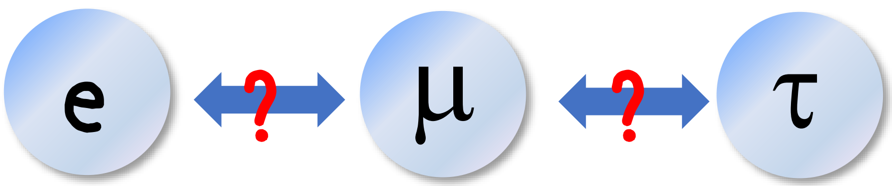
COMETちゃん
(HiggsTanより)

Introduction

Lepton Flavor Violation (LFV)



Experimentally verified
=> neutrino oscillation



Never observed yet !!

Standard Model (SM) + ν mass:

Branching ratio (BR) $\sim O(10^{-54})$ Impossible to observe…

> **Discovery of charged LFV → beyond SM**

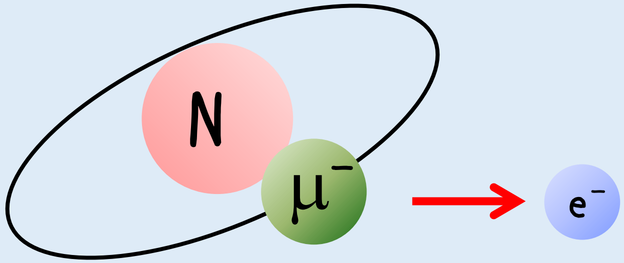
Beyond SM (SUSY-GUT, SUSY-SEESAW, etc.):

BR $\sim O(10^{-15})$ **Achievable!**

Introduction

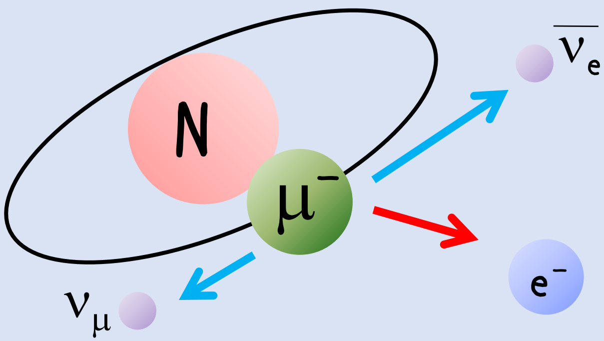
muon to electron conversion $\mu^- N \to e^- N$

Signal



- mono-energetic electron
  $E_e = m_\mu - B_\mu \sim 105$ MeV (N=Al)
- Coherent process

BGs



- Decay in Orbit (DIO)
- Radiative π/μ-capture
- Decay in Flight (DIF)
- Cosmic-rays など

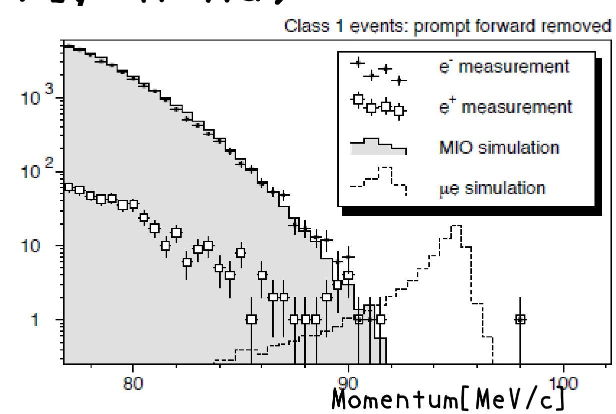
Current limit BR < 7×10^{-13} (SINDRUM-II@PSI, N=Au)

Issues

① high intensity (HI) μ beam

② BG reduction

③ high res. detector

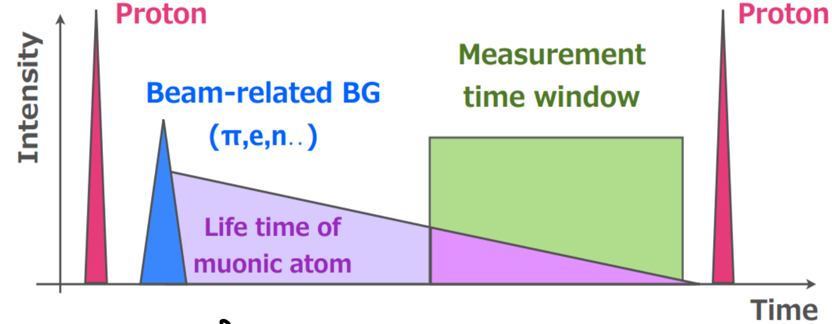


COMET experiment

Search for μ-e conversion@J-PARC

Solutions

① J-PARC high intensity beam
② Pulsed beam, Transport solenoid
③ New detector



Beam structure

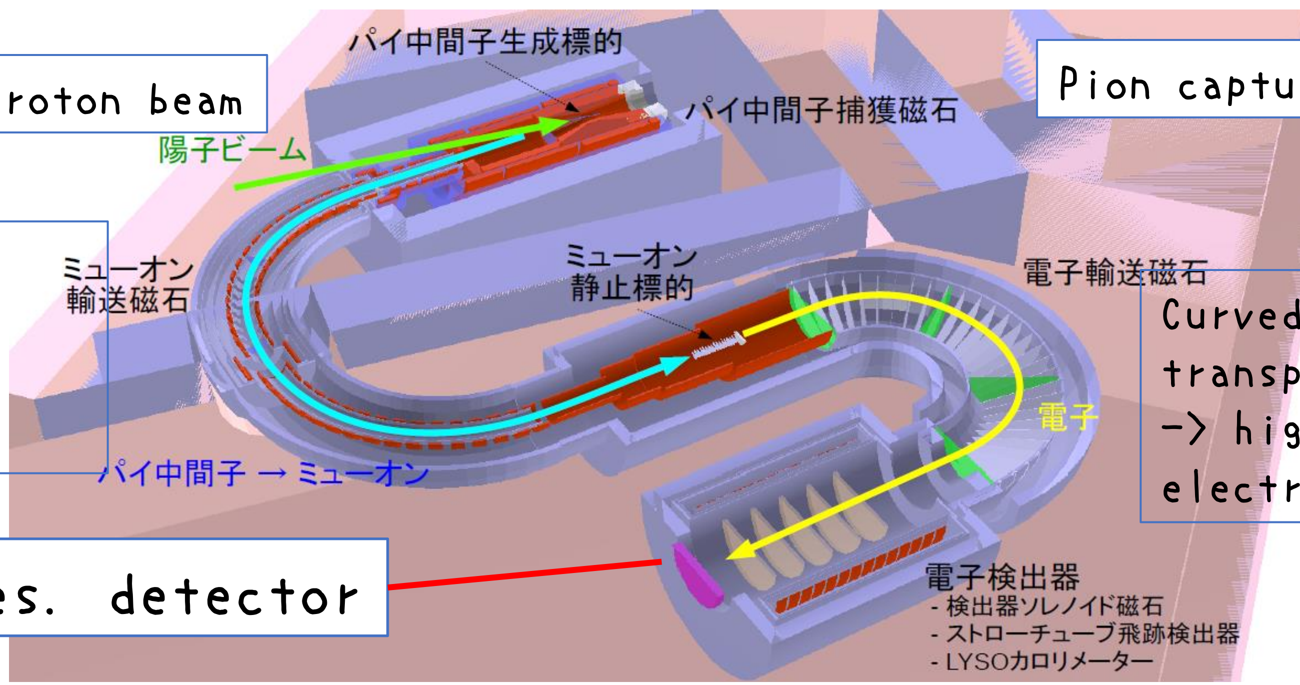
HI pulsed proton beam

Pion capture solenoid

Curved π/μ solenoid -> low momentum μ

Curved electron transport solenoid -> high momentum electron

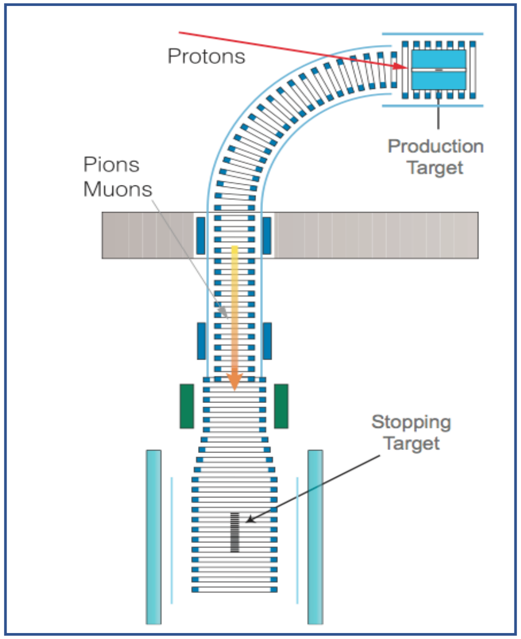
High res. detector



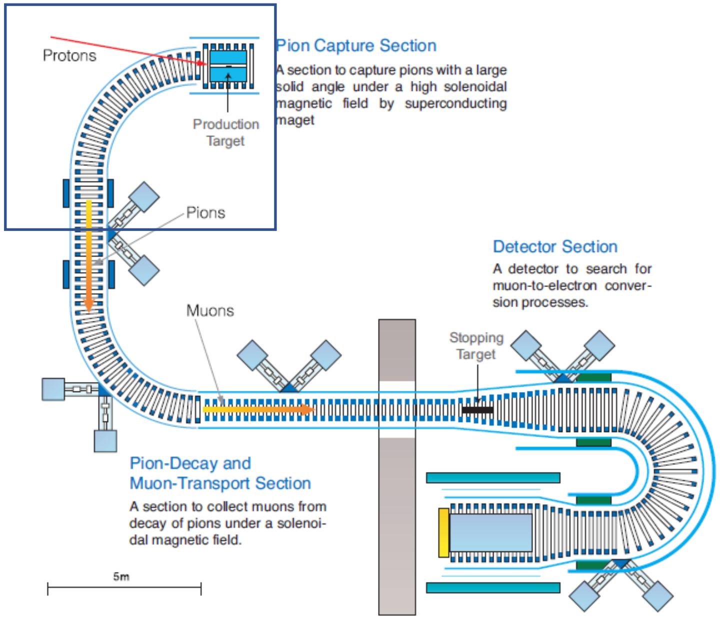
Goal sensitivity (SES) : 3 x 10^{-17} (x10000 better)

COMET experiment

Staging approach



Phase-I (2023)



Phase-II (202?-)

Phase-I

1. R&D for Phase-II

   Beam measurement ⇒ Phase-II detector

2. μ-e conversion search

   SES $O(10^{-15})$ (x100 better) ⇒ another detector

2 detector systems

Detector1:CyDet (Cylindrical Detector System)

CDC (Cylindrical Drift Chamber)

electron tracking -> momentum

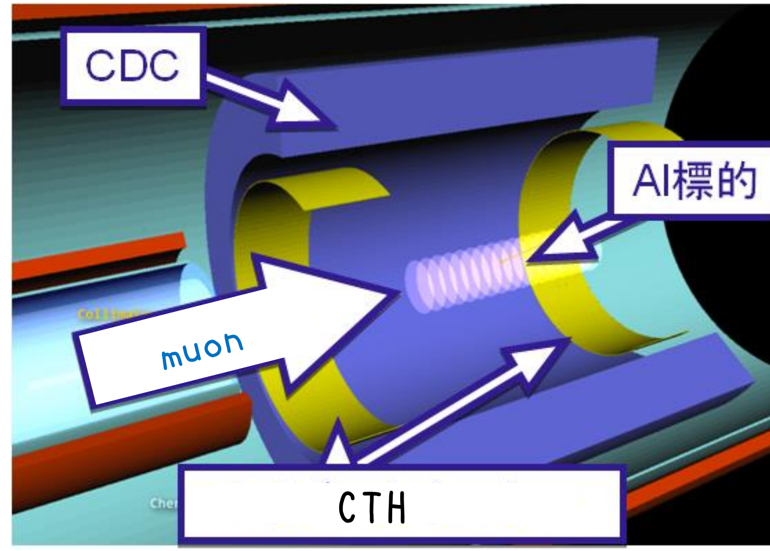
momentum res. < 200 keV/c @ 105 MeV/c

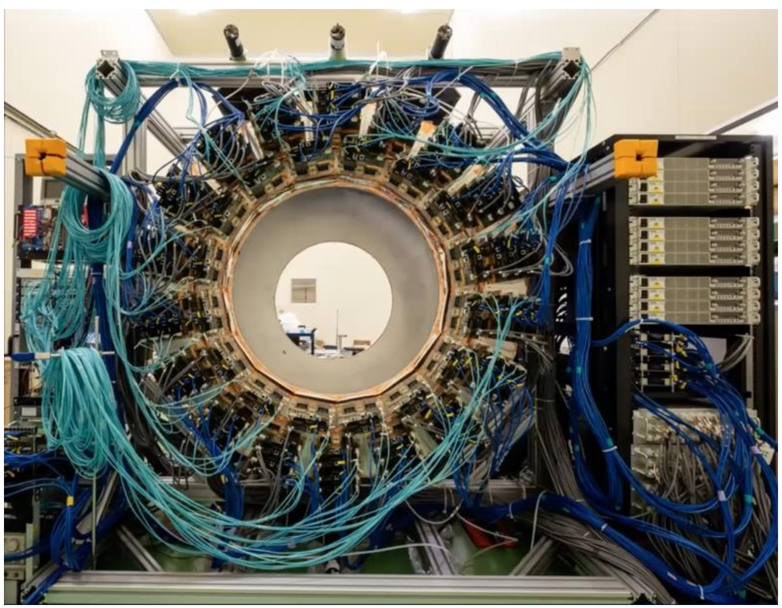
CTH (Cylindrical Trigger Hodoscope)

trigger detector

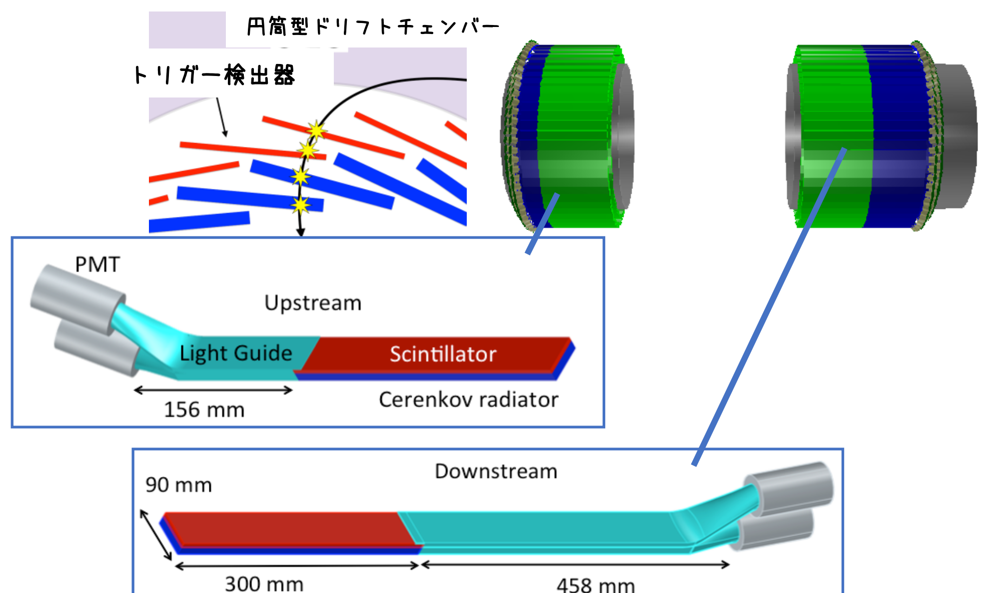
scintillator (+ Cherenkov detector)

photon detector : **fiber+MPPC**





CDC



CTH

Detector2 : StrECAL

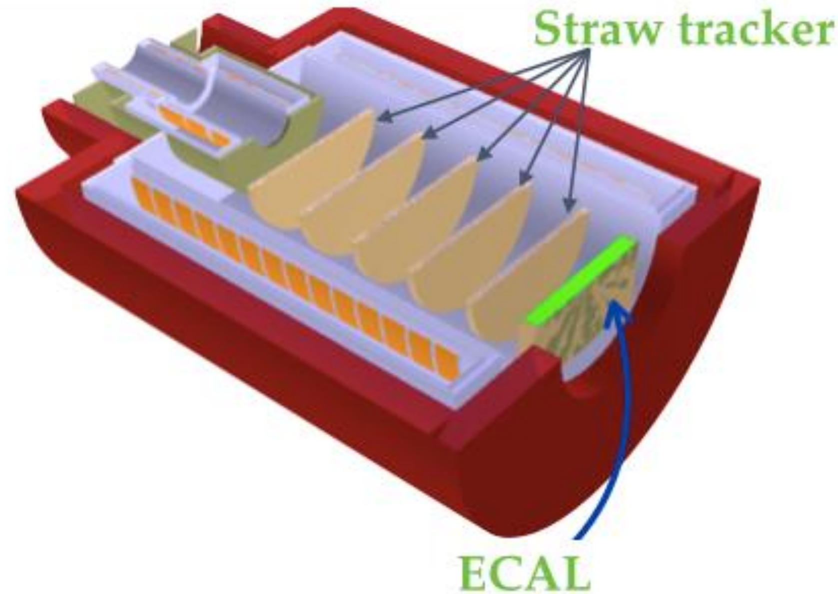
(Straw tube tracker + Electron calorimeter)

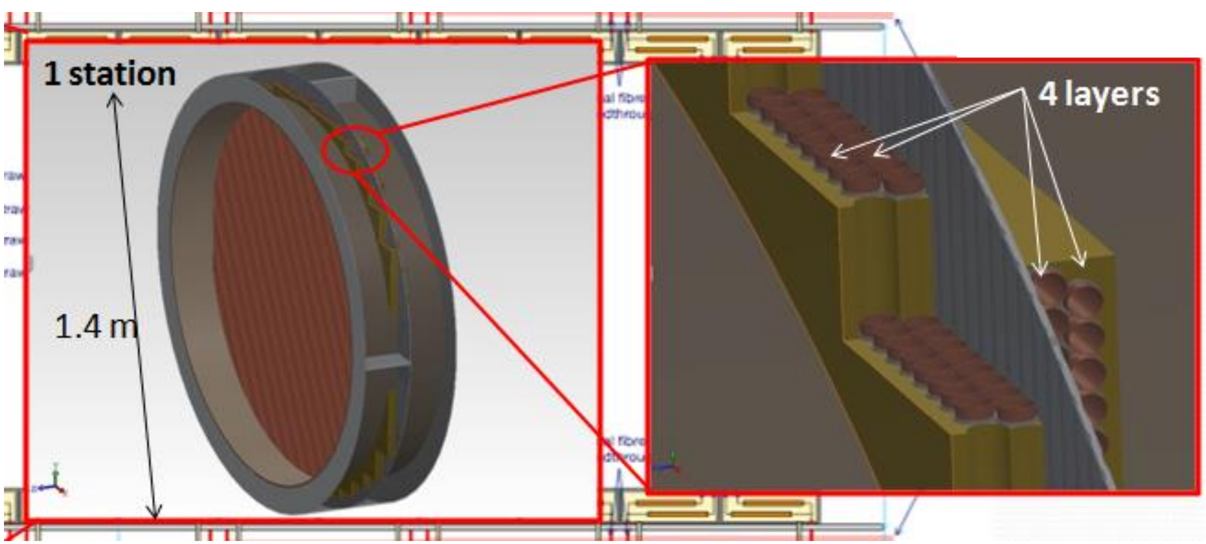
Straw tube tracker

- electron tracking -> momentum
- **momentum res. < 200 keV/c @ 105 MeV/c**

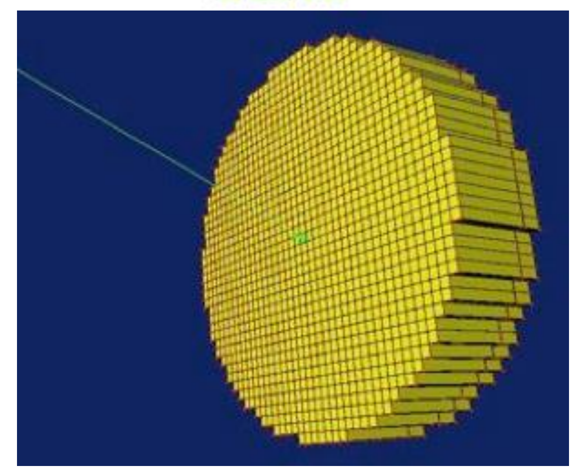
Ecal (Electron Calorimeter)

- LYSO + APD
- Energy, timing, position
- trigger, PID



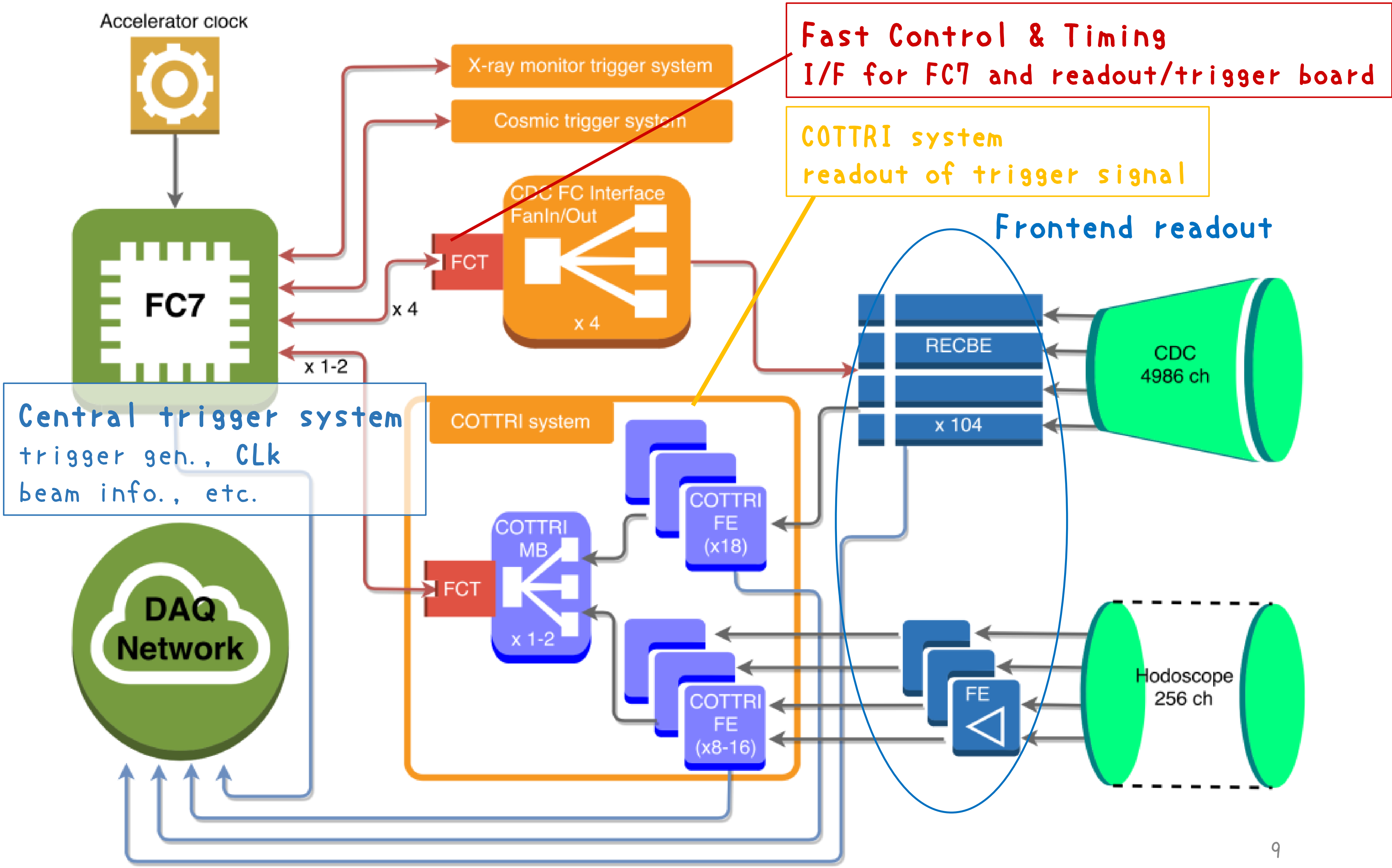


Straw tube tracker

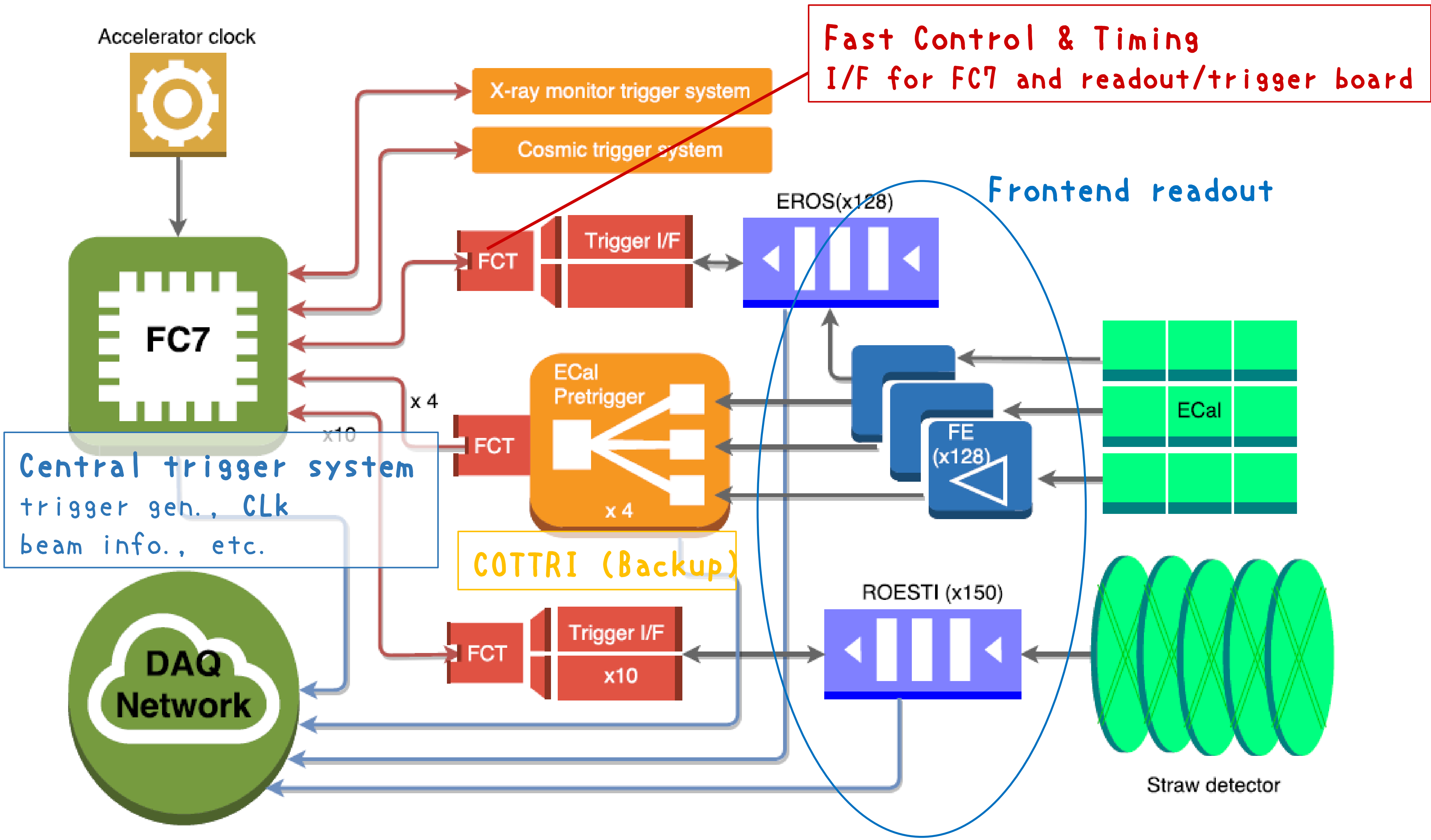


ECal

Measurement system(CyDet)



Measurement system(StrECal)



Electronics developments

COMET needs following electronics:

- Central trigger system
- Fast Control & Timing board (FCT)
- CDC FE readout
- CTH FE readout
- Trigger readout
- Straw readout
- Ecal FE readout
- Ecal readout

Blue: Japan in charge

It is hard to construct all boards from scratch.

- use technical asset and develop necessary parts
- **utilize Open-It**

* each detail was reported in past workshops.

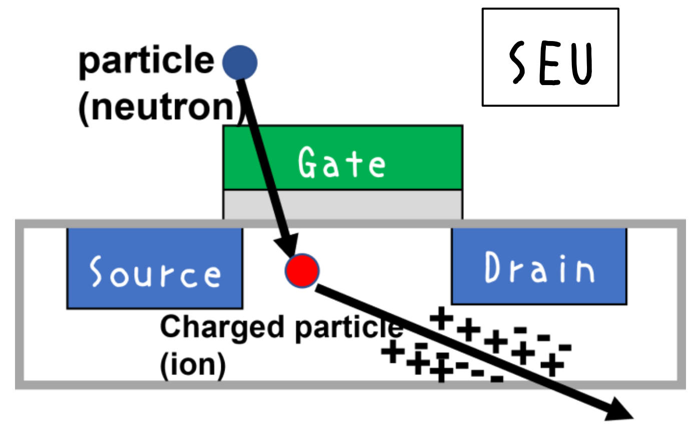
Issues

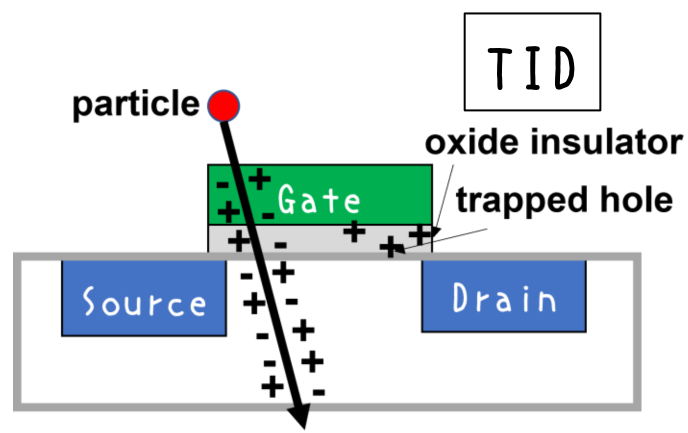
High intensity beam experiment

- High rate →M. Miyataki(next talk)
- High radiation →this talk

Radiation effects

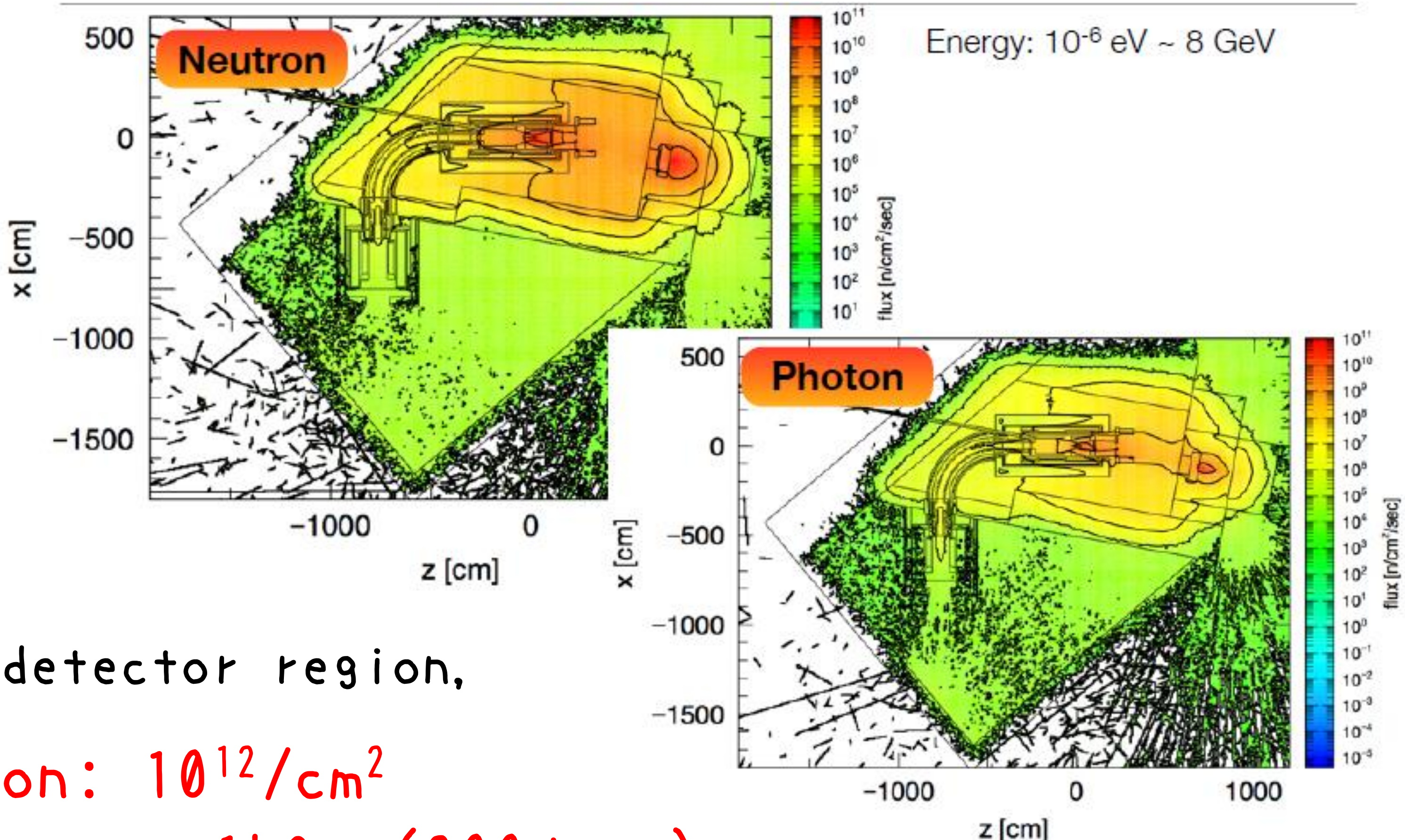
- Single Event Upset(SEU)
  - Bit flip by neutron (nuclear reaction, recoil) and high energy heavy particles.
  - FPGA, flash memory
- Type Inversion
  - Hard damage in semiconductor by neutron.
  - semiconductor devices, transistor
- Total Ionizing Dose Effect (TID)
  - Permanent damage by fixed charge from large amounts of radiation (gamma-ray).
  - regulator, SFP
- Displacement Damage Dose (DDD)
  - Permanent damage by displacement of crystal lattice atom from radiation (electron, proton, large amounts of neutrons).





Radiation level @ COMET

- PHITS calculation for Phase-I



At the detector region,

neutron: $10^{12}/cm^2$

gamma-ray: 1kGy (200days)

(w/ safety factor)

Our efforts

- Simulation studies
  - PHITS, Geant4, FLUKA, MARS
- SEU
  - SEU rate measurement@Kobe Tandem facility
  - SEU detection/correction
    - Configuration RAM
      - SEM(IP core from Xilinx)
      - Firmware re-download when UnRecoverable Error (URE) occurring
    - Block RAM
      - Error Correction Code (ECC) (IP core from Xilinx) using Hamming code
      - Cyclic Redundancy Check (CRC)
- TID, DDD
  - irradiation tests

➡ We managed to pass (almost) all the tests for Phase-I.

For details, see my slide in previous workshop.

Towards the future

- In Phase-II, beam intensity will increase by about 20 times.

  -> radiation issues will be severer.
- (Maybe some groups concerns similar issues.)
- We have to come up with a solution.

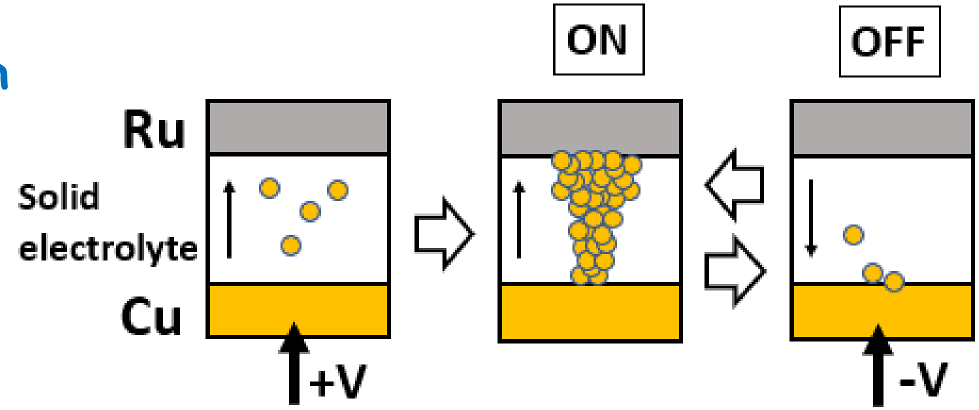
- Example : Using Atom switch

  -> NanoBridge FPGA

Atom switch

Domestic non-volatile switch

Conductive bridge is formed in polymer solid electrolyte between 2 electrodes.



Specification

resistances	:	ON/OFF～2k/200M Ω
# of rewriting times	:	>10^3
retention time	:	> 10 years
Switch capacitance	:	< 0.2 fF
SEU free in principle		

NanoBridge(NB) FPGA

from NBS

removed

NanoBridge FPGA

from NBS

removed

NanoBridge FPGA

from NBS

removed

NanoBridge FPGA

from NBS

removed

NanoBridge FPGA

- Features
  - Rad-hard (error rate < 1/100)
  - Low power consumption (< 1/10)
- Current status
  - irradiation test with heavy ion and pulsed laser
  - verification test on satellite

In principle OK for our purpose

We need to confirm feasibility.

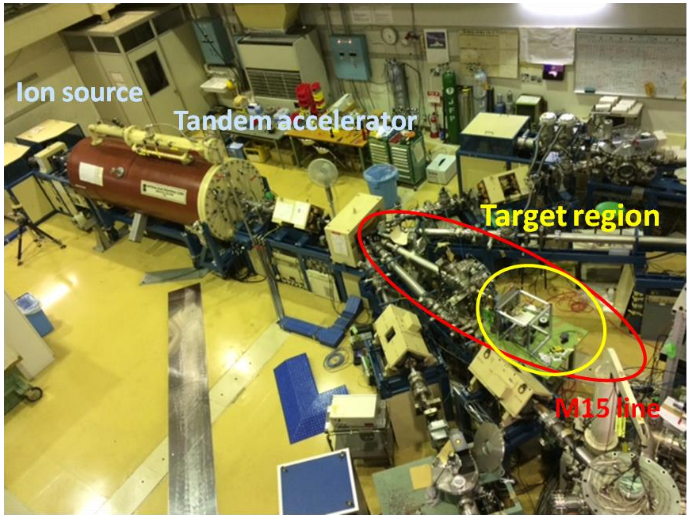
- tolerance to very high radiation level
- usability
- etc...

Irradiation tests

Neutron irradiation tests

Tandem accelerator @ Kobe Univ.

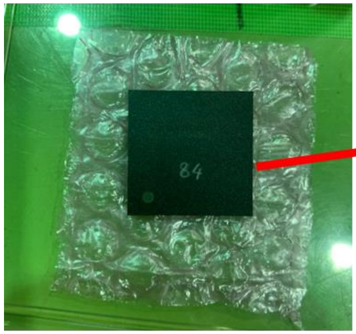
- Beam : 3 MeV deuteron
- Target : Be (ϕ20 mm)
- Neutron energy : 2 MeV (<7 MeV)
- Flux : 4.9×10^6 Hz/cm^2 @ 10cm from target (beam current = 1 μA)



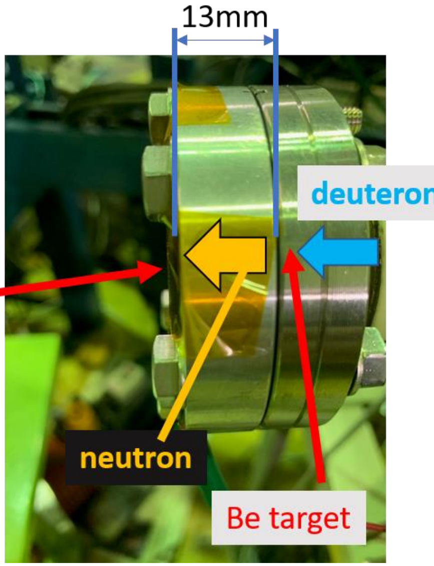
Tandem facility

Reactor @ KUR

- Method : Pneumatic Tube
- Rated thermal power : 5 MW
- Neutron energy : broad
- Flux : > 10^{13} Hz/cm^2



Packaged AS-FPGA

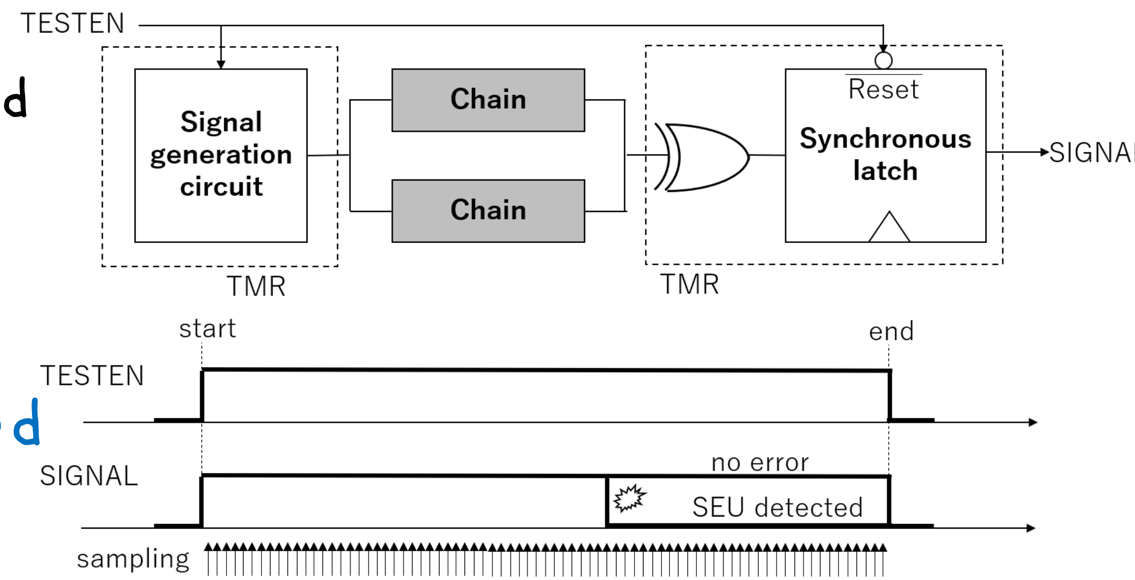


SEU and DDD measurements

Neutron irradiation tests

SEU counts were measured with 4 types of chains.

NO SEUs were observed in NB!



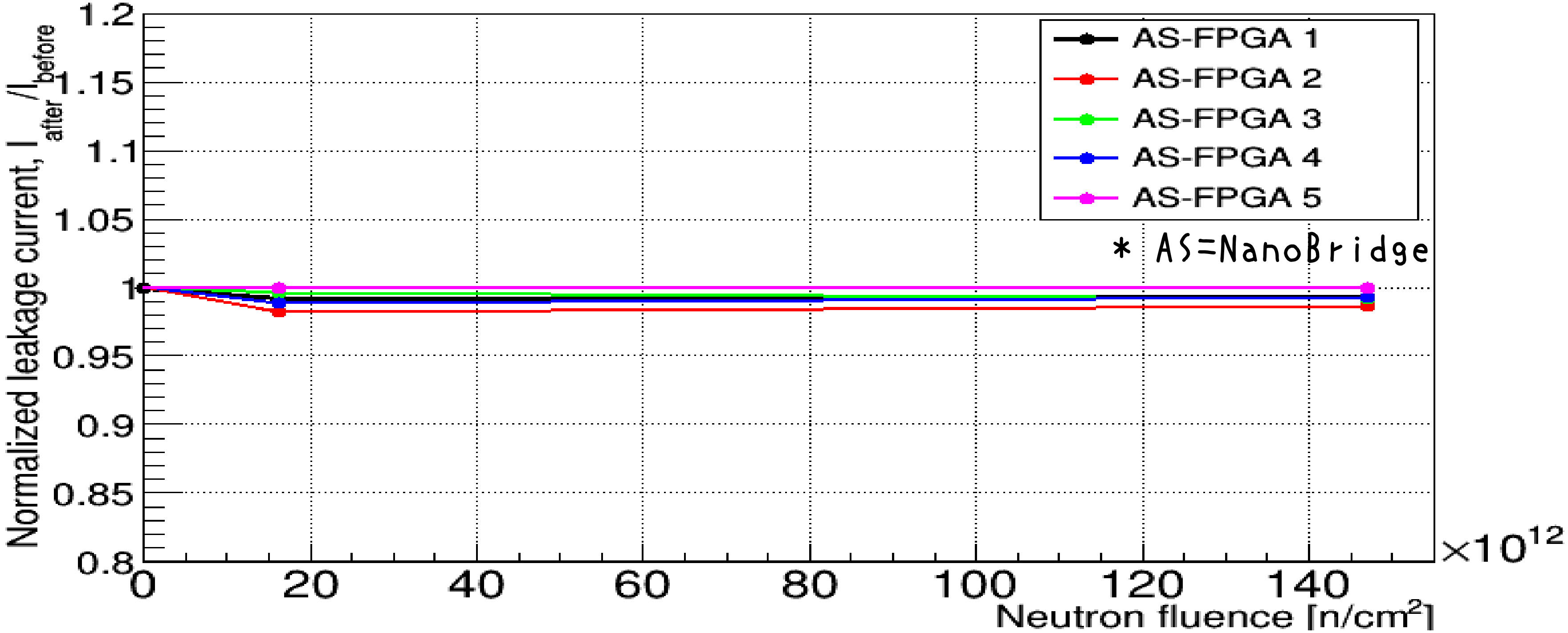
Schematic view of evaluation circuit for SEU

Results of SEU counts

DUT type	Scale	Neutron fluence(n/cm^2)	SEU counts
SRAM	2 kbit	1.6×10^{11}	5
NB1	96 CLBs	3.6×10^{11}	0
NB2	368 CLBs	1.7×10^{11}	0
DFF+AS	468 CLBs	1.5×10^{11}	0

Neutron irradiation tests

Leakage current was measured before/after irradiation.



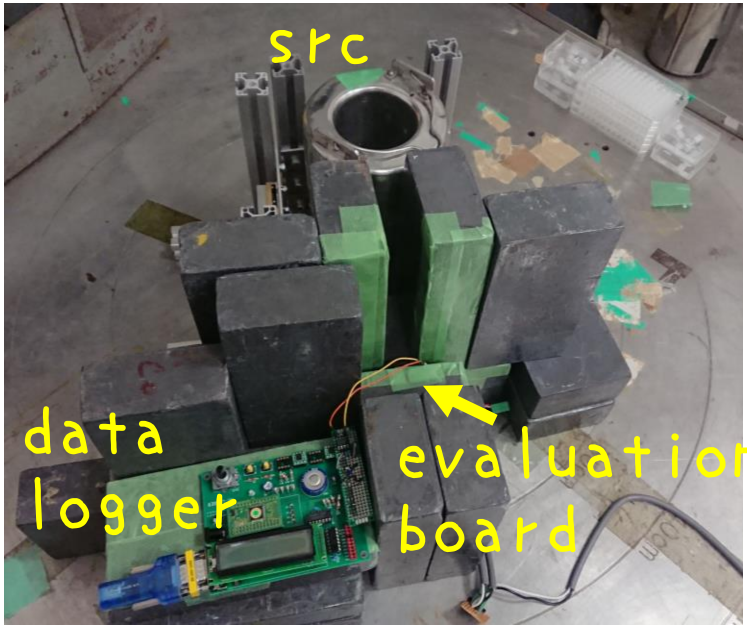
NO DDDs were observed!

Irradiation tests

gamma-ray irradiation tests

RI Center @ Tokyo Institute of Technology & QST

- Src : Co-60
- Dose rate : 500 Gy/h
- Total dose : 10 kGy

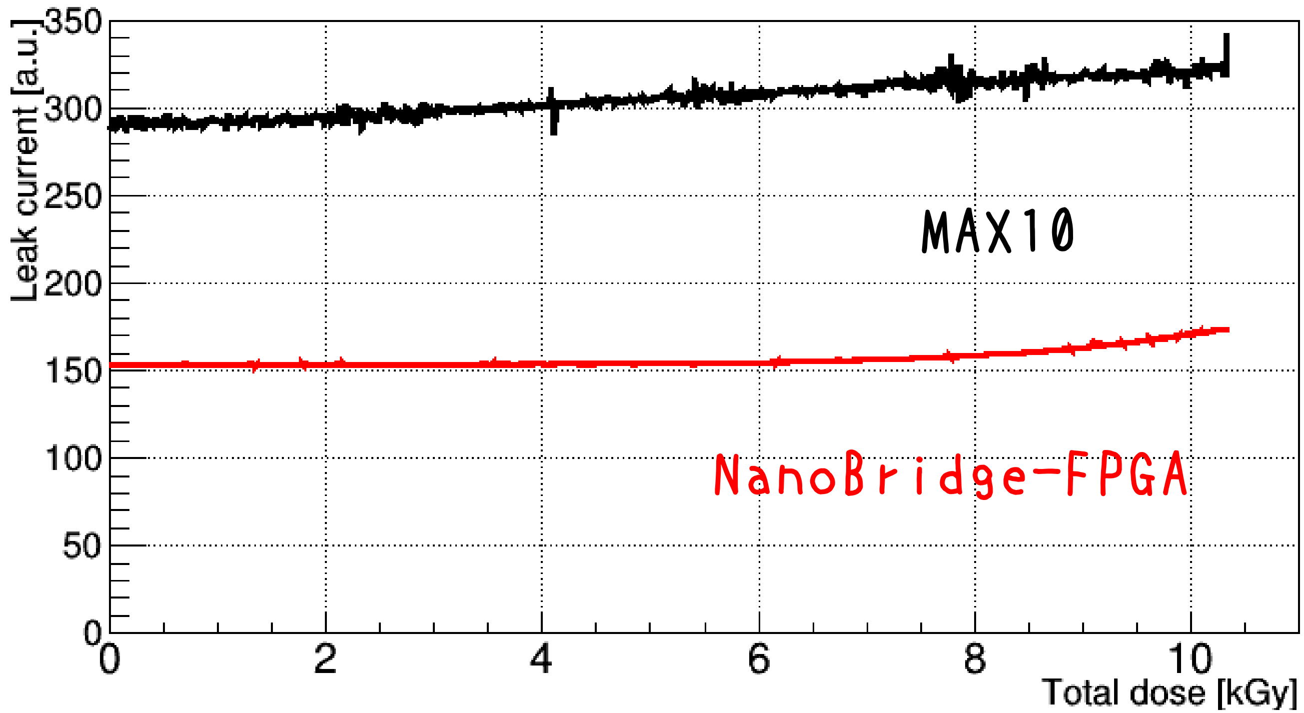


Experimental setup

TID measurements

gamma-ray irradiation tests

Leakage current were measured during irradiation.



NO change was seen up to 6 kGy.

After 6 kGy, leakage current increased slightly due to degradation in CMOS.

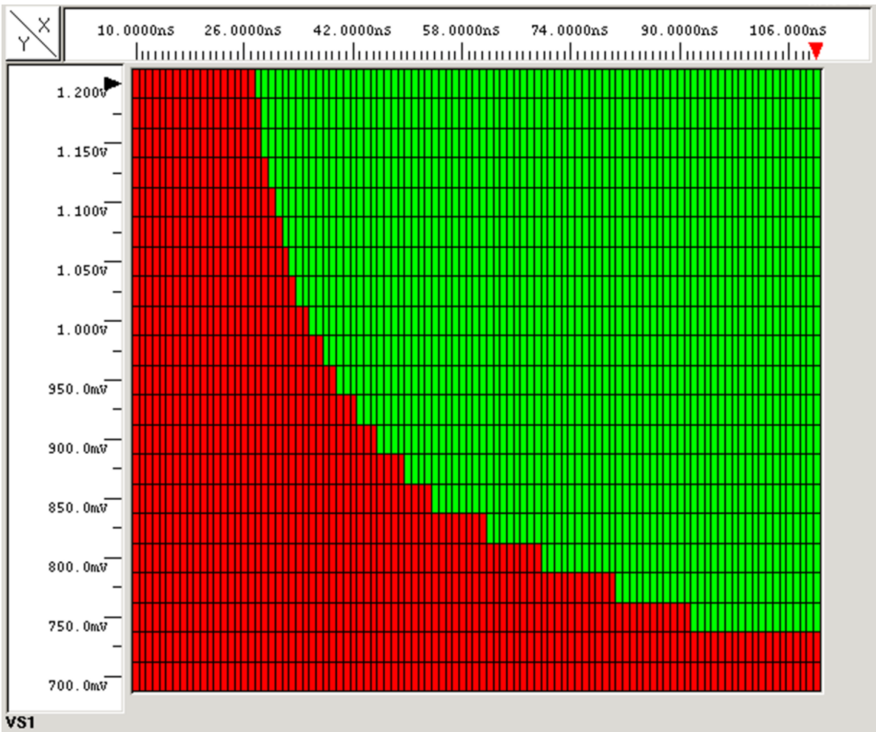
gamma-ray irradiation tests

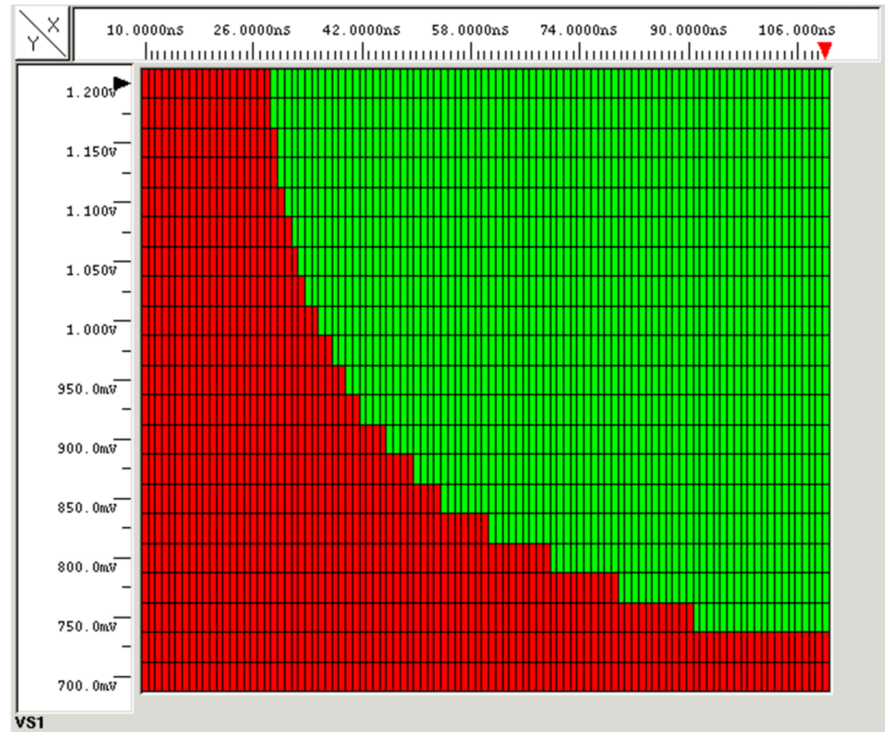
Shmoo plot

before irradiation

after 10 kGy irradiation

operation voltage[V]





operation clk period [ns]

operation clk period [ns]

NO change in signal delay was seen after 10 kGy irradiation.

Future works

It was found that NB-FPGA had potential to use for our experiment.

- (Irradiation tests with higher level)
- Construction of evaluation board
- and more...

Let me know if you are interested in the development.

Summary

- Preparation of COMET experiment is ongoing.
- Many parts of electronics development use Open-It.
- We have 2 issues due to high intensity beam.
  - rate -> next talk
  - radiation -> almost passed for Phase-I
- NB-FPGA is one candidate to use for COMET Phase-II (and other future experiment?).

Buckup

SEU rate

	CRAM		BRAM	
	SEU $[[n/cm^2]^{-1}]$	URE $[[n/cm^2]^{-1}]$	SEU $[n/cm^2]^{-1}\ kB^{-1}$	MBE $[[n/cm^2]^{-1}\ kB^{-1}]$
Virtex-5	$(4.6 \pm 1.4) \times 10^{-8}$	$(1.4 \pm 0.4) \times 10^{-10}$	$(7.0 \pm 2.2) \times 10^{-11}$	$(9.7 \pm 3.1) \times 10^{-13}$
Artix-7[1]	$(3.4 \pm 1.0) \times 10^{-8}$	$(1.2 \pm 0.4) \times 10^{-11}$	$(7.6 \pm 2.3) \times 10^{-12}$	
Artix-7[2]	$(2.9 \pm 0.9) \times 10^{-8}$	$(5.4 \pm 1.7) \times 10^{-11}$	$(7.0 \pm 2.3) \times 10^{-12}$	$(1.4 \pm 0.6) \times 10^{-12}$
Kintex-7	$(2.6 \pm 0.8) \times 10^{-8}$	$(5.7 \pm 1.8) \times 10^{-11}$	$(8.7 \pm 2.7) \times 10^{-12}$	

Y. Nakazawa et al., NIMA, 936, 351(2019)

ついでに

2017 計測システム研究会　発表スライドより

技術・資産の共有化

- そんなわけで放射線対策は中々大変
- 各グループでそれぞれやるのは非効率
- 日本には情報共有の場がない
- 開発もそんなに進んでいない（宇宙は別）
- 今後（特に大強度加速器実験等では）更に必須になってくる技術

Open-Itを利用して共有の場を展開したい

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技術・資産の共有化

- ひとまず「枠」は作ってみました
- http://openit.kek.jp/project/RADHARD/RADHARD
- （とりあえず公開はしてます。）

取り組み

- 情報共有
  - 民生用パーツ、マテリアル等の放射線耐性試験結果
  - 耐放射線パーツ、マテリアル等の開発の動向
  - 耐放射線検出器の現状
  - 各機関、グループにおける取り組み
  - 参考になる論文、資料等のまとめ
- 開発
  - SEU対策FPGAファームウェア
  - 新たな耐放射線パーツ、マテリアル開発
- ワークショップ、セミナー
  - 各グループのスタディについての議論
  - 専門家によるセミナー

興味ある方は→　http://openit.kek.jp/project/RADHARD/RADHARD