Present Status and Future Prospects of COMET to Search for μ-e Conversion at J-PARC

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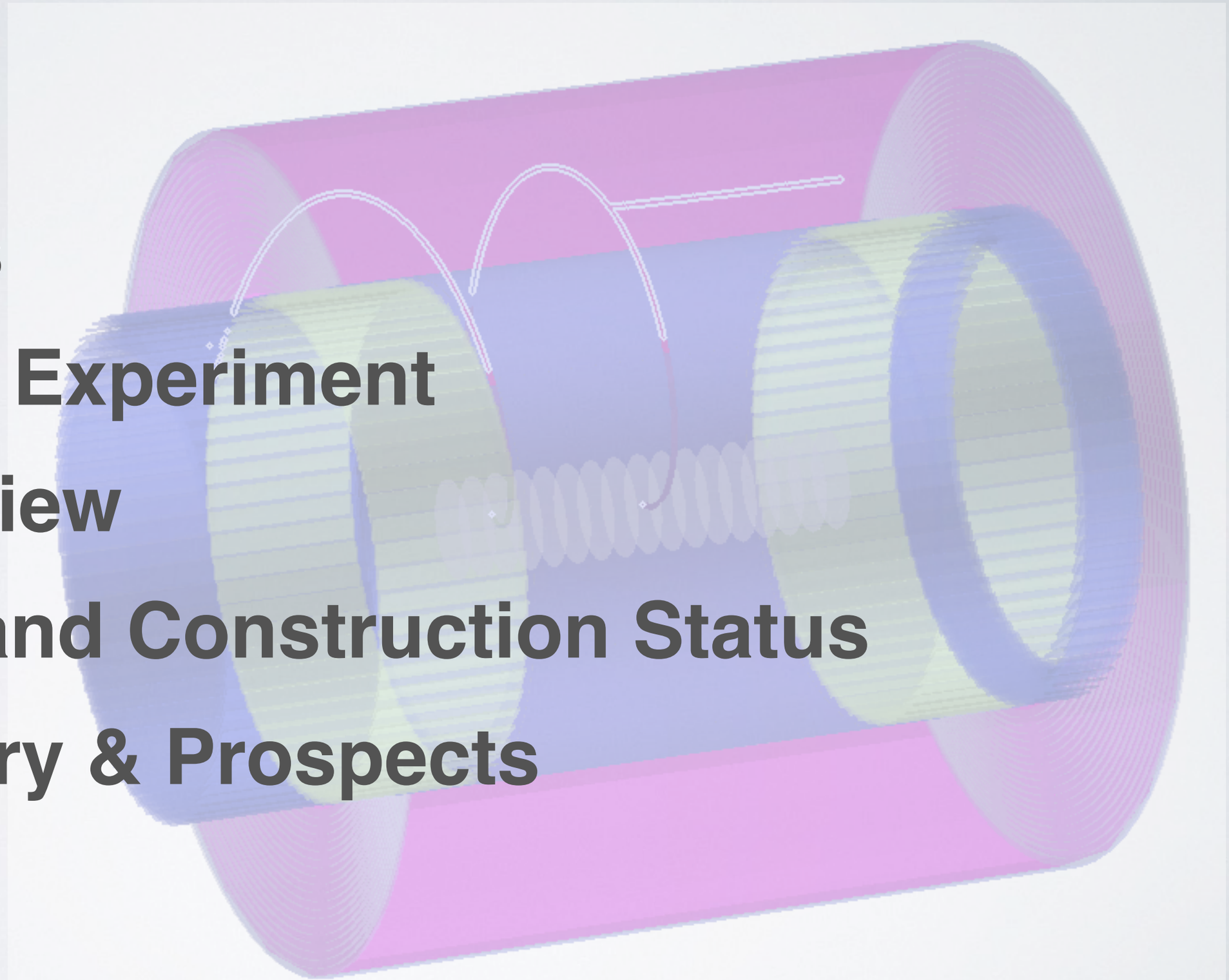
KEK
on behalf of the COMET Collaboration
CLFV2016, Charlottesville, 21st June 2016

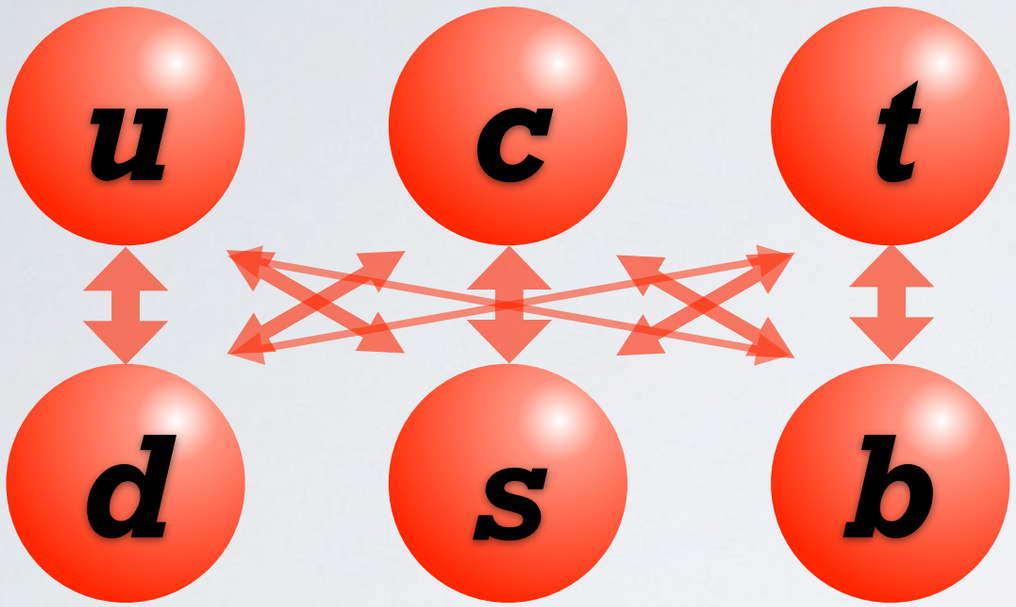
Outline



- Physics
- COMET Experiment
  - Overview
  - R&D and Construction Status
- Summary & Prospects

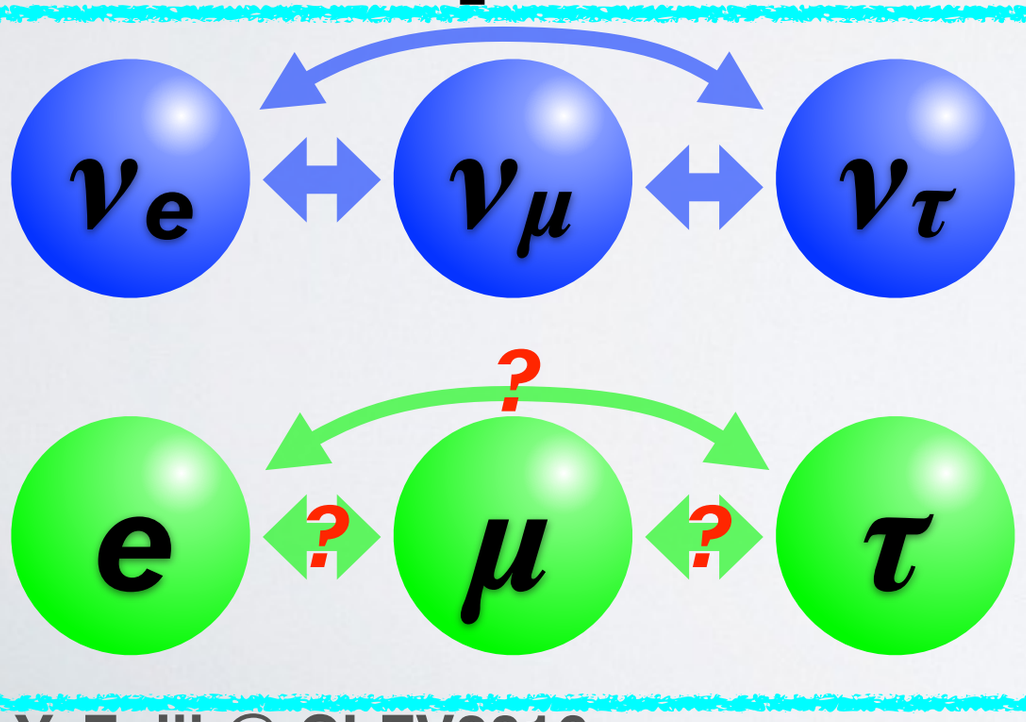
Physics

Quarks



Flavors are mixed through CKM matrix in the Standard Model,
Already confirmed

Leptons

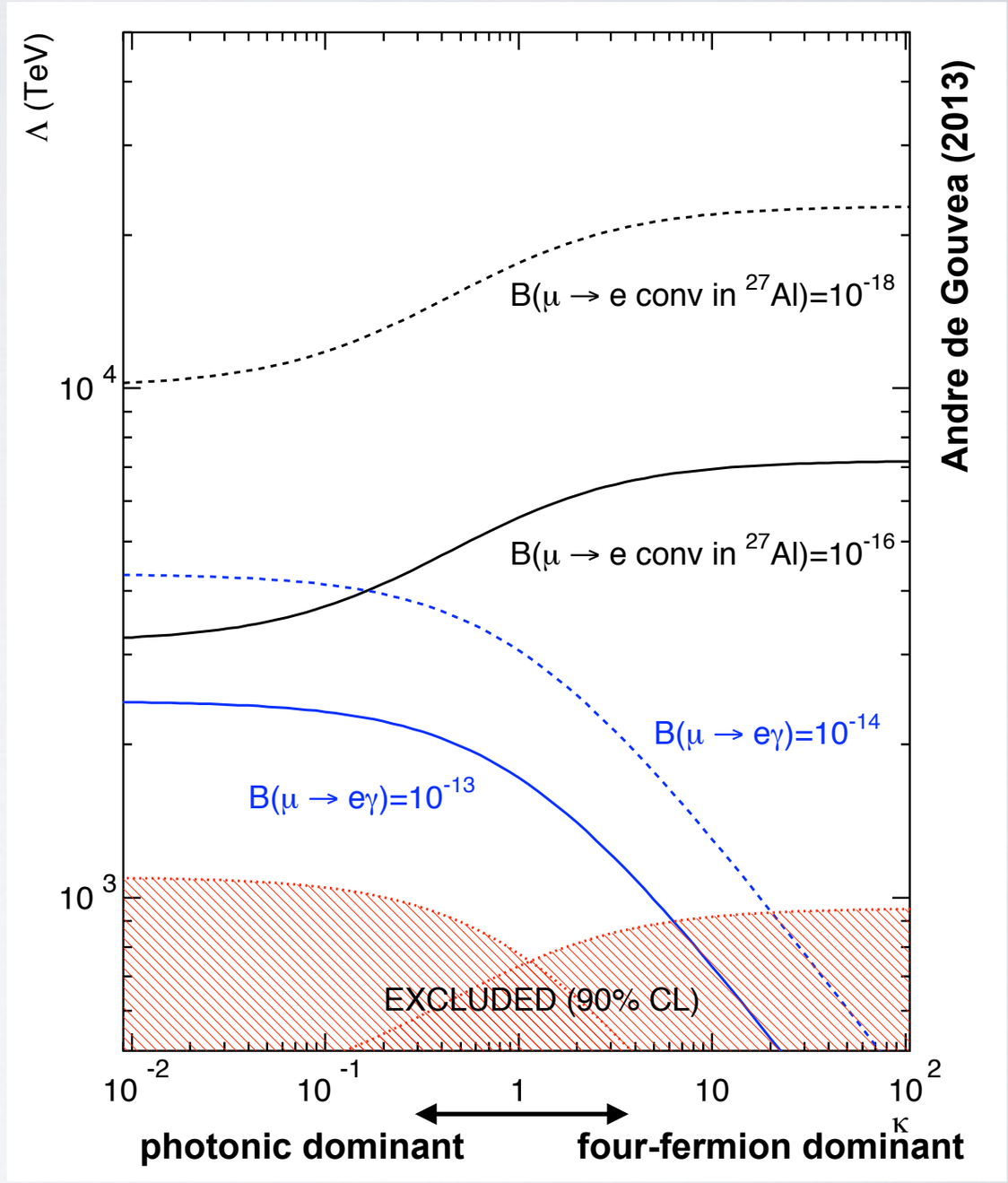


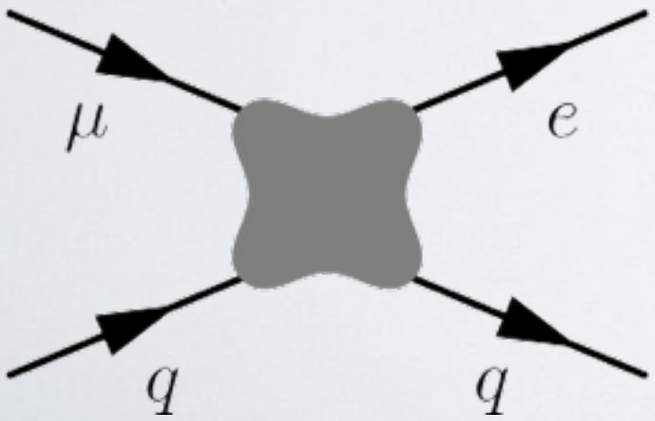
Flavors are mixed through PMNS matrix,
Already confirmed (extension of SM)

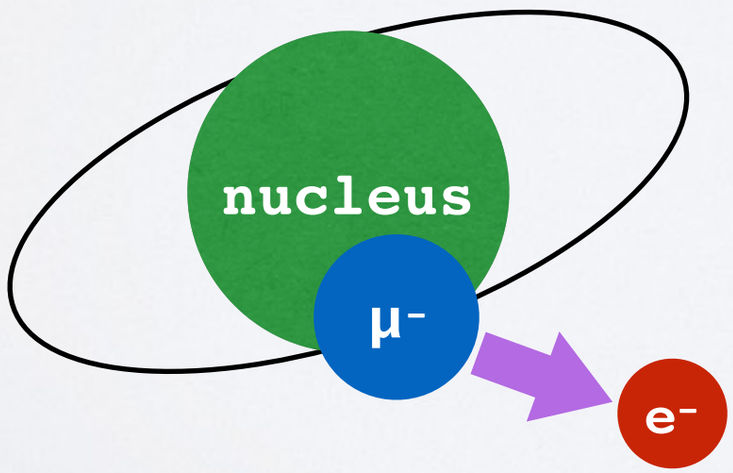
Charged Lepton Flavor Violation
Forbidden in the Standard Model,
$B(\mu \to e\gamma) \sim O(10^{-54})$ for SM+ν oscillation,
Not observed so far

μ-e Conversion

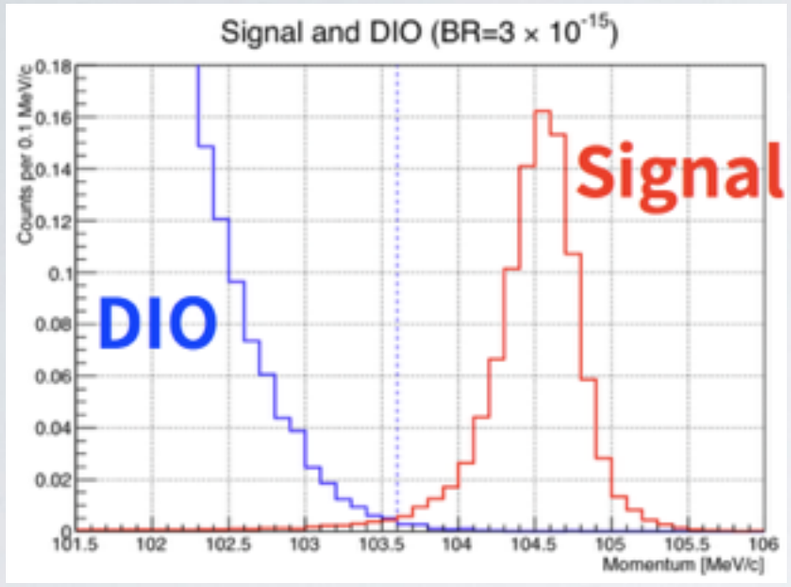
- Muon to electron conversion in nuclei w/o neutrino emission
  - ~O(10^{-54}) in SM + ν-oscillation
  - Enhanced in many BSMs
  - **Observation → New Physics**
- Simple kinematics: $E_e=M_\mu-B_\mu\sim104$MeV
- LHC, other CLFV searches, muon g-2 are complementary



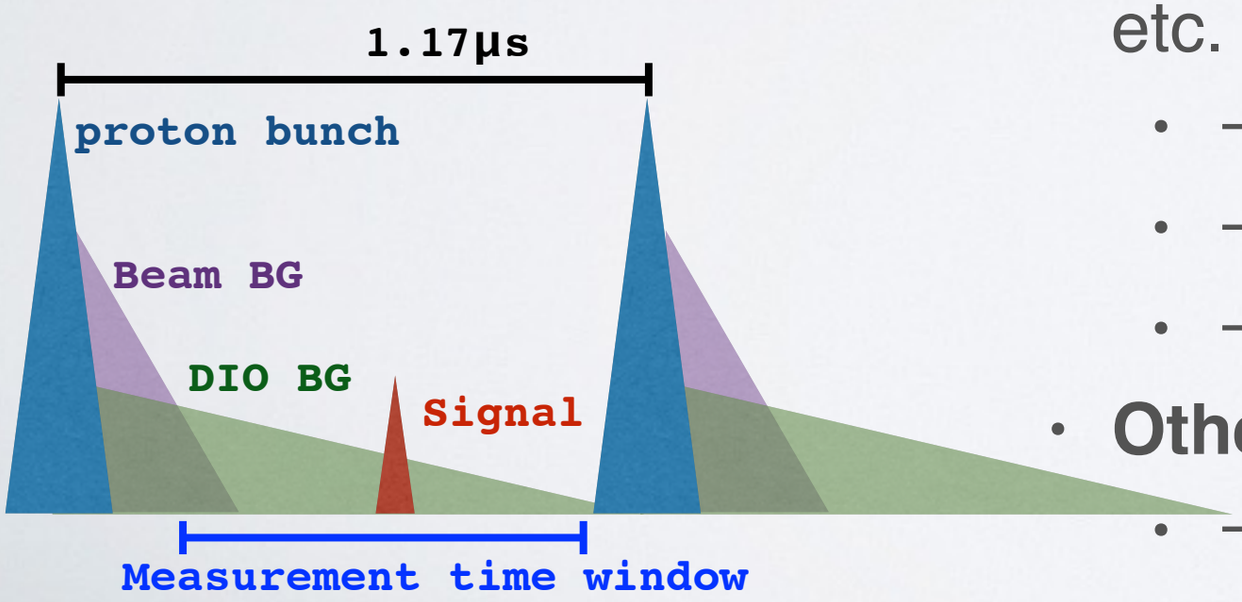




Requirements



$$\text{Extinction} = \frac{\text{Number of protons between 2 bunches}}{\text{Number of protons in a bunch}}$$



- **High statistics**
  - $>10^{17}$ of stopping muons are required
    - → High intensity proton beam @J-PARC
    - → π/μ collection using capture solenoid
- **Background suppression**
  - **Intrinsic BG**: Muon DIO (Decay In Orbit)
    - → Excellent momentum resolution
  - **Beam BG**: Radiative pion capture, Muon decay in flight, Antiproton, Proton leakage, etc.
    - → Pulse beam + delayed time window
    - → Good extinction factor (less than 10^{-9})
    - → Curved solenoid
  - **Other BG**: Cosmic ray
    - → Add detector for cosmic ray veto


μ
COMET
e

COMET Collaboration

- International collaboration composed of 175+ researchers of 33 institutes from 15 countries

The COMET Collaboration

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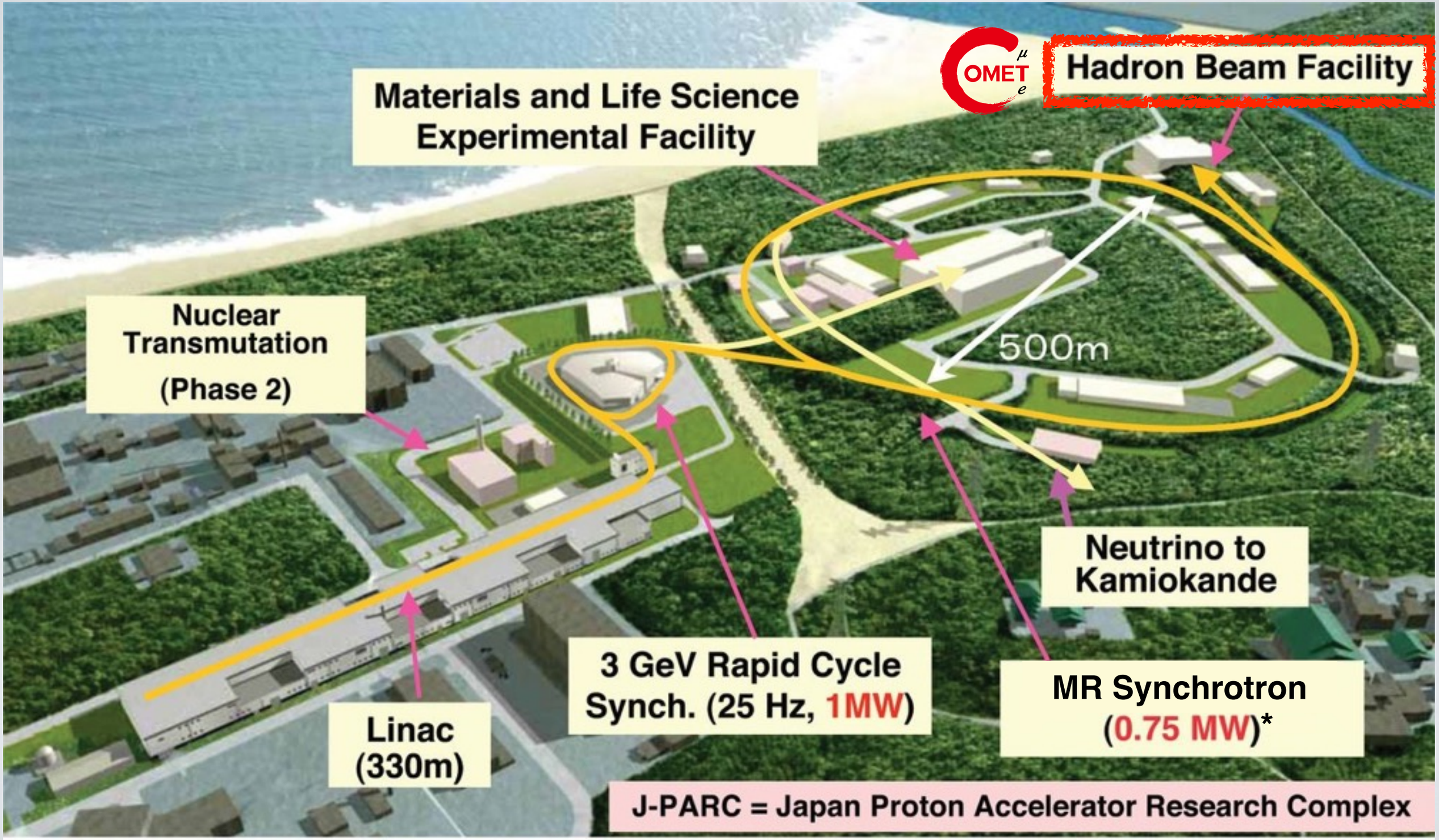
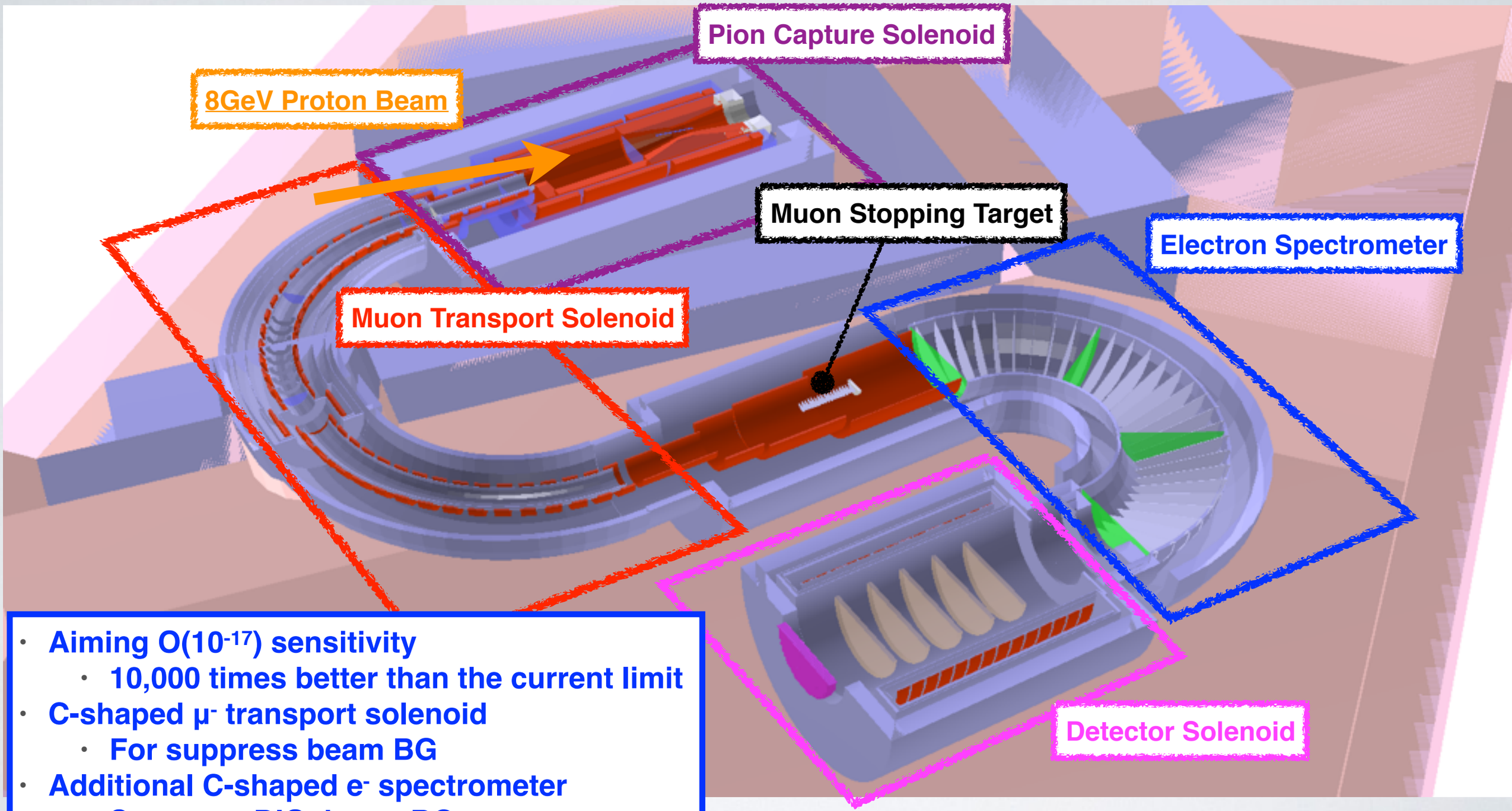
J-PARC



Joint Project between KEK and JAEA

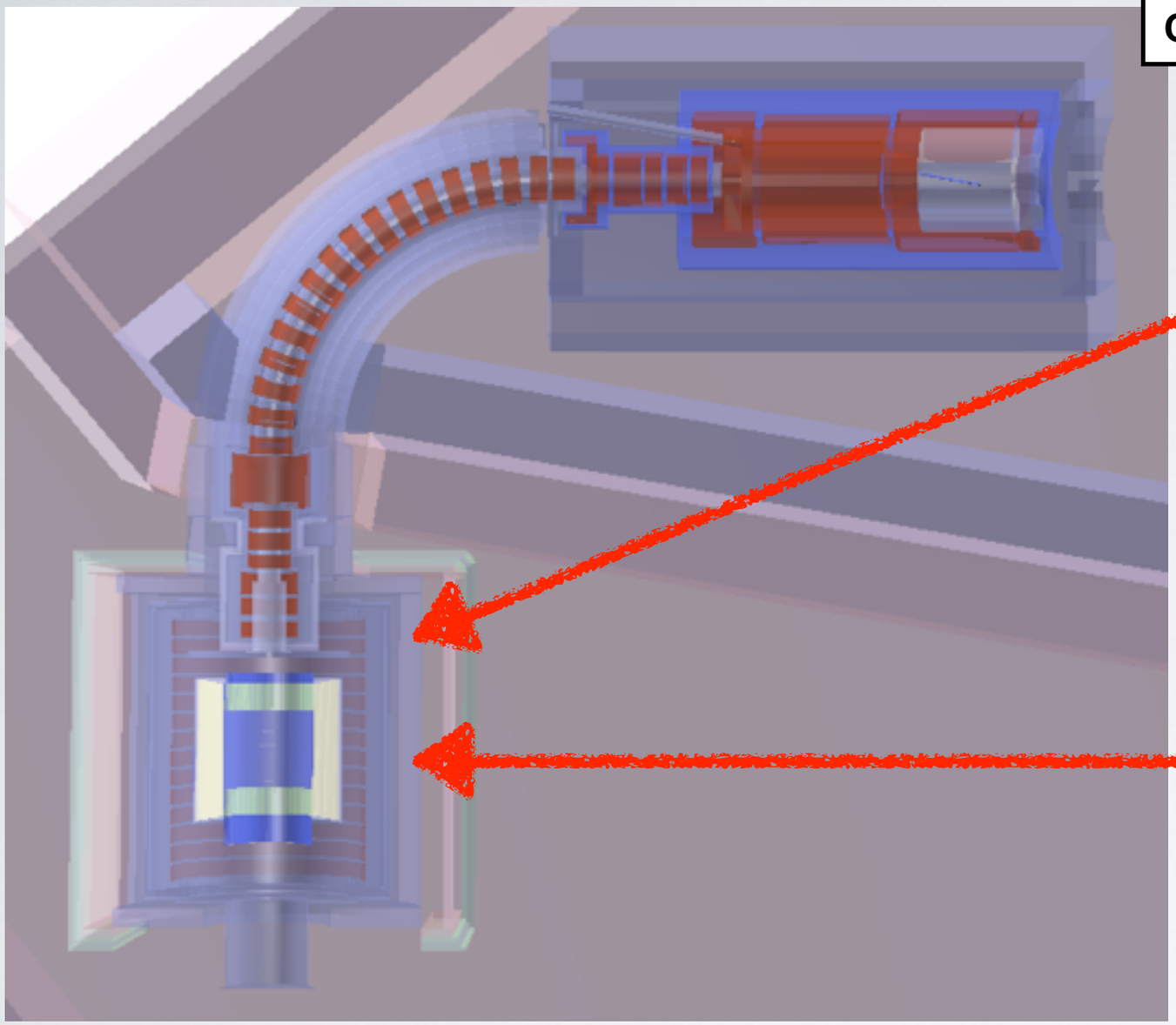
*design value

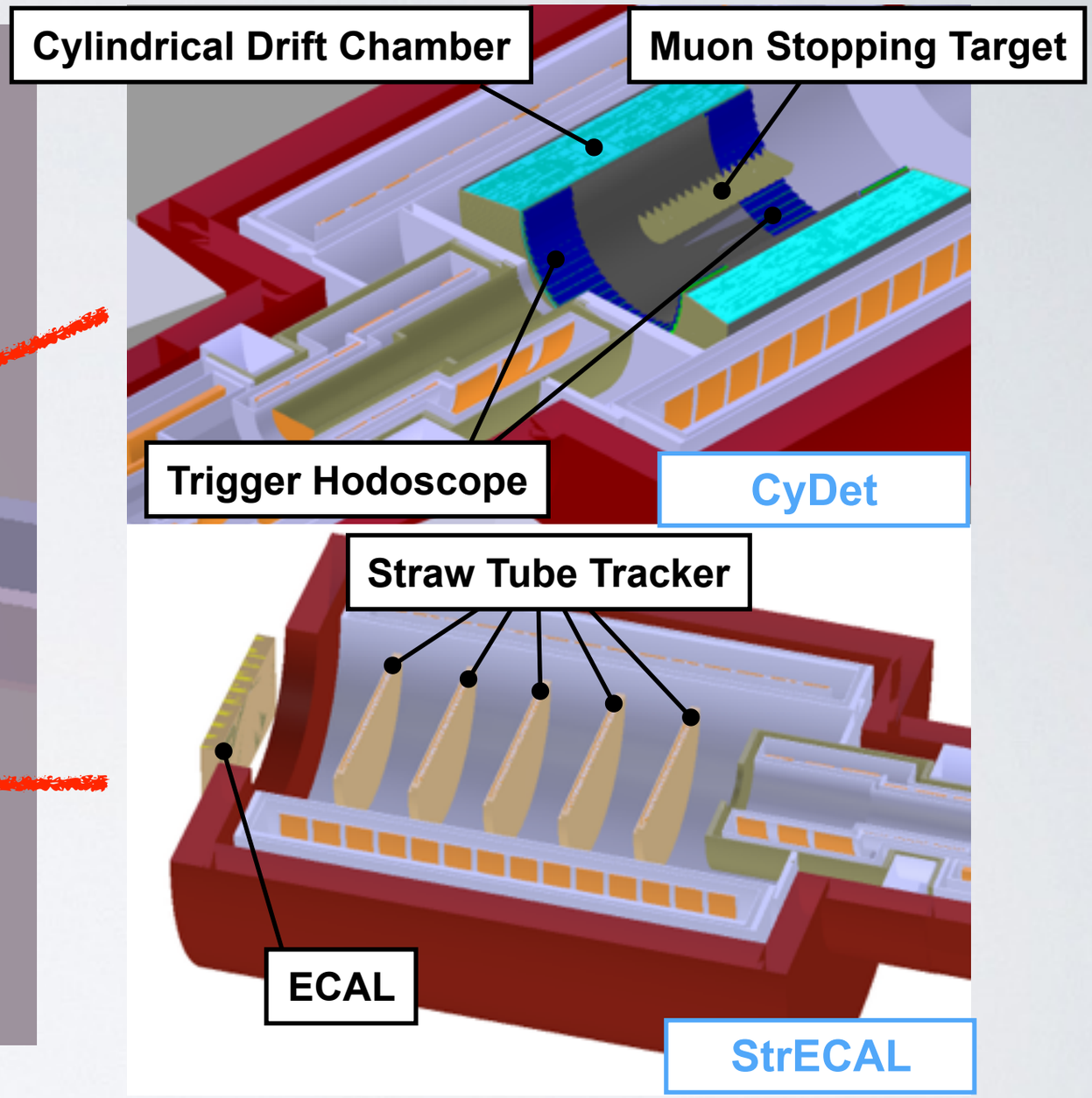
COMET Overview



- Aiming O(10^{-17}) sensitivity
  - 10,000 times better than the current limit
- C-shaped μ^- transport solenoid
  - For suppress beam BG
- Additional C-shaped e^- spectrometer
  - Suppress DIO+beam BG

COMET Phase-I

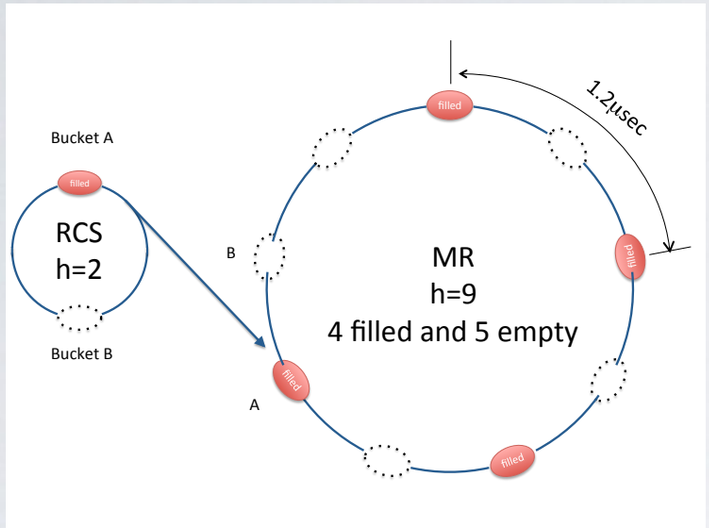


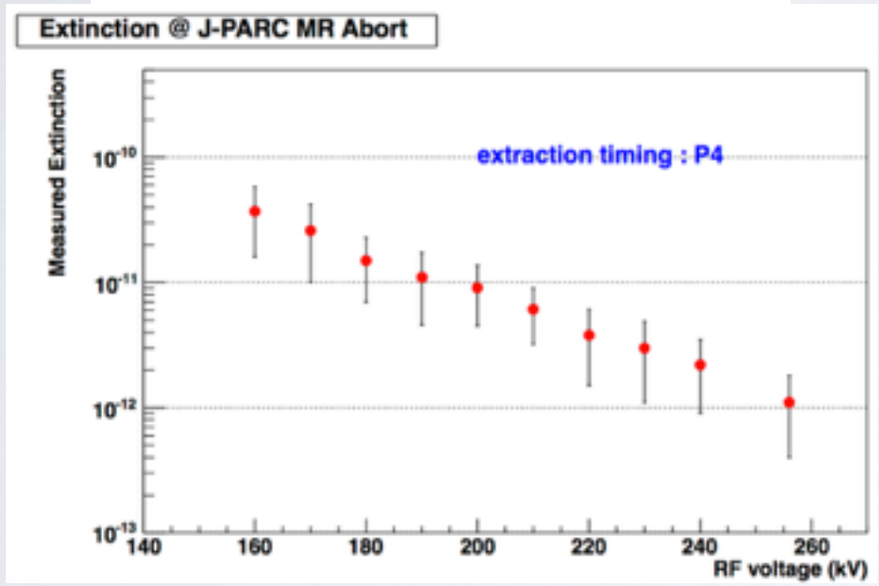


- Construct the first 90 degree of the muon transport solenoid
- Perform the μ-e conversion search with a sensitivity of 10^{-15} using **CyDet**
- Measure the beam directly using **StrECAL** as a Phase-II prototype detector

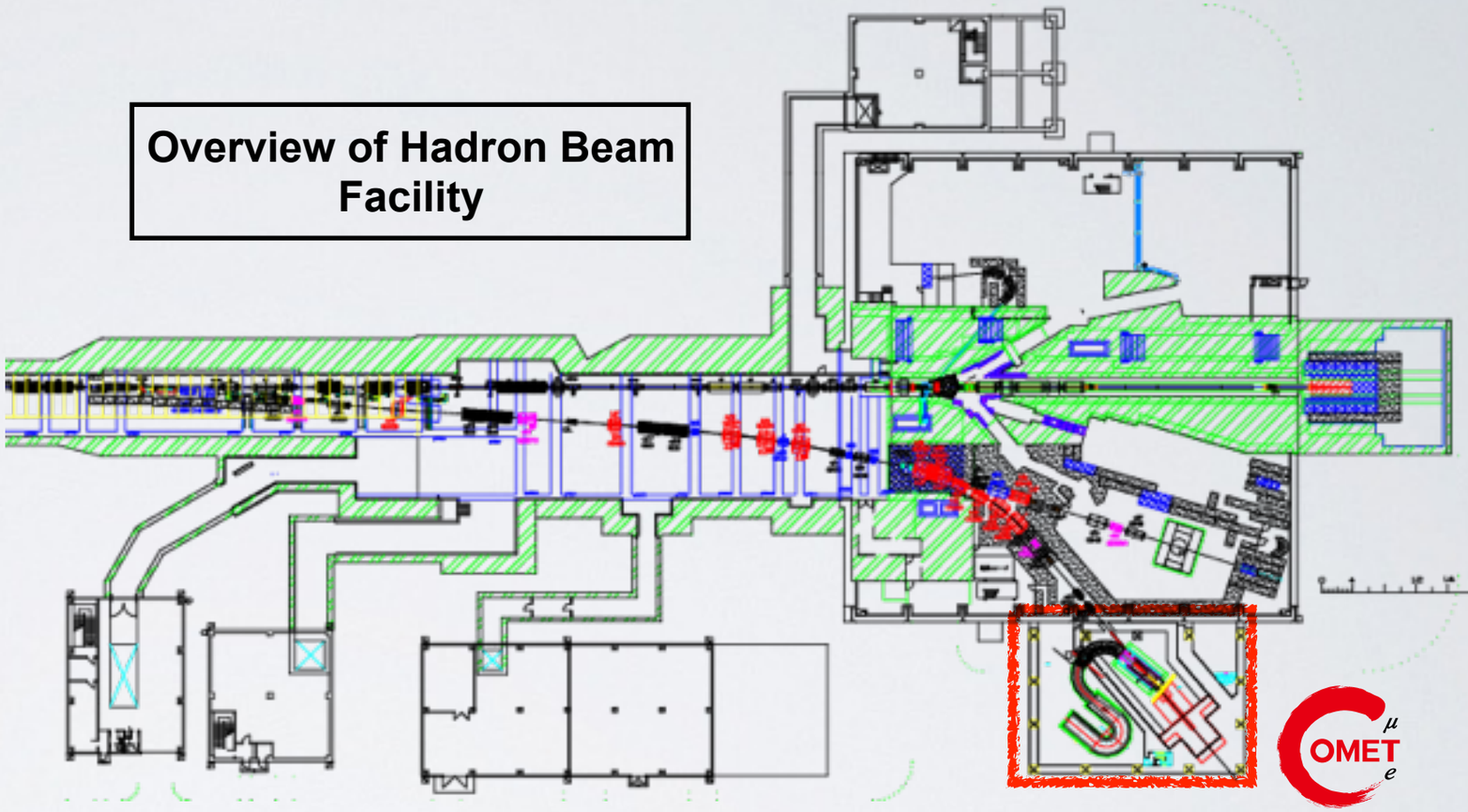
Beam and Facility

Proton Beam





Overview of Hadron Beam Facility



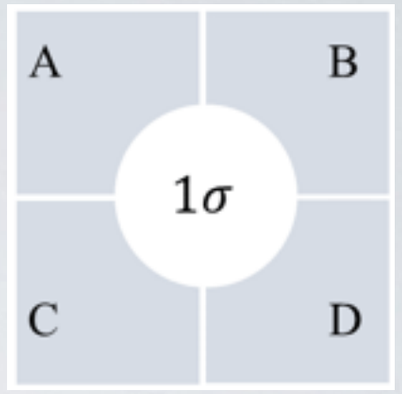
- Bunched slow extraction with a 3.2(56) kW operation in Phase-I(Phase-II)
- Beam pulsing with a 1.17μs interval using “Single Bunch Kicking” method
- Accelerate protons up to 8GeV in MR → Deliver them to COMET hall @ Hadron Beam Facility
- Extinction factor already measured to be 3×10^{-11} even in the worst case

COMET Hall

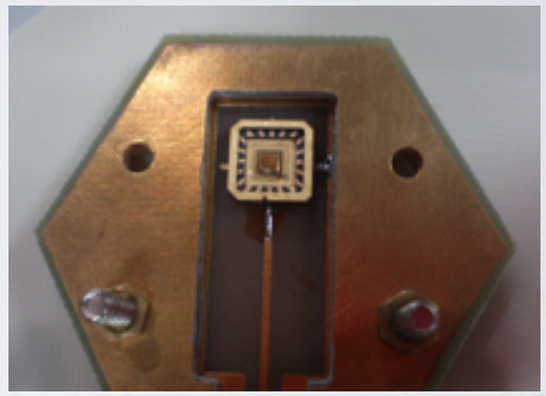
- COMET hall
  - Construction **completed** in last year
- High-p/COMET beam line
  - Construction and Engineering design ongoing

Proton Monitor/Target

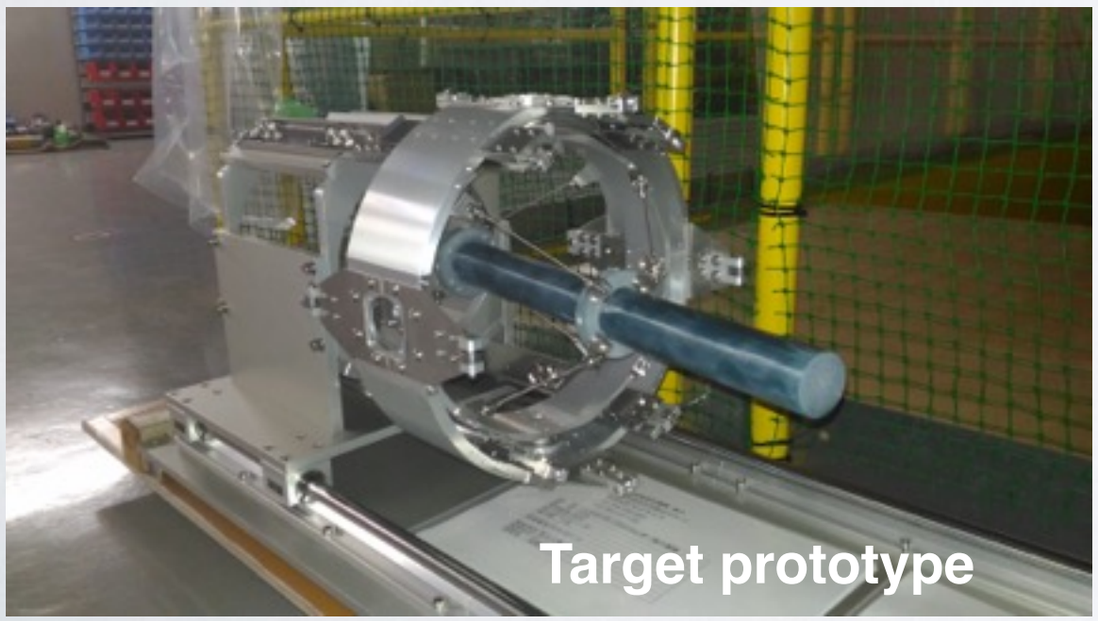
- **Proton monitor**
  - Measure the beam profile/extinction in front of the capture solenoid
  - Use the **innovative diamond detector**
    - High radiation tolerance & Fast time response
    - First beam test for diamond prototype is ongoing @J-PARC MR
      - **Clear signals synchronized with beam bunch observed**
- **Proton target**
  - Graphite(or SiC)/Tungsten target for Phase-I/Phase-II
  - Geometry optimized to increase the stopping muon yields, **R=13mm, L=700mm**

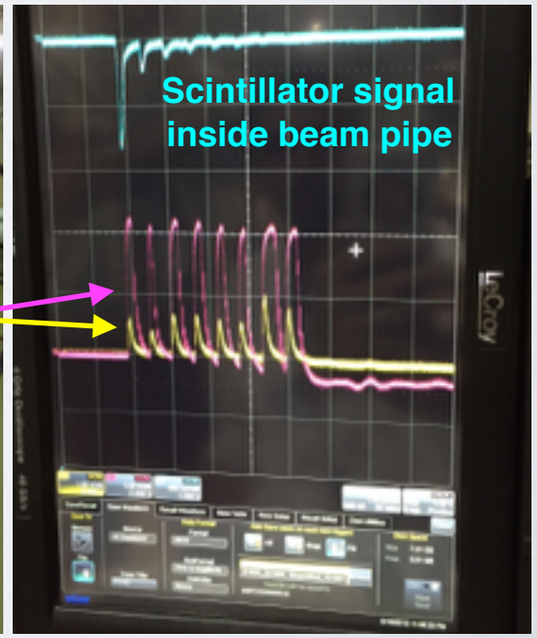


Geometry of proton monitor



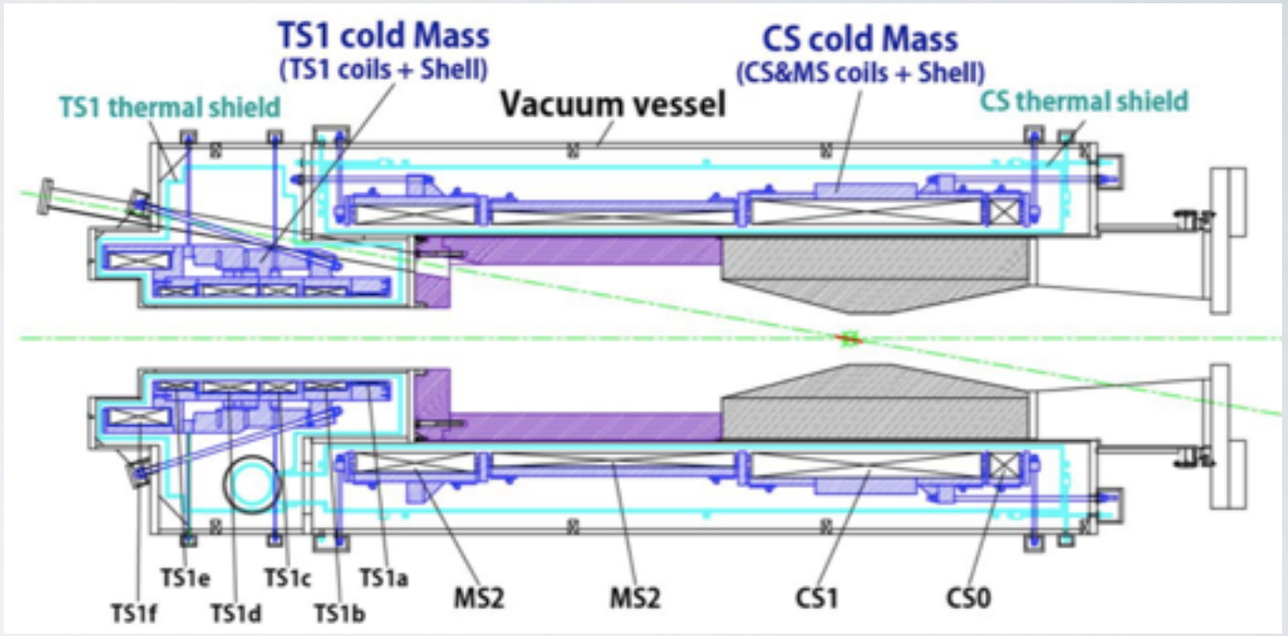
Diamond prototype detector

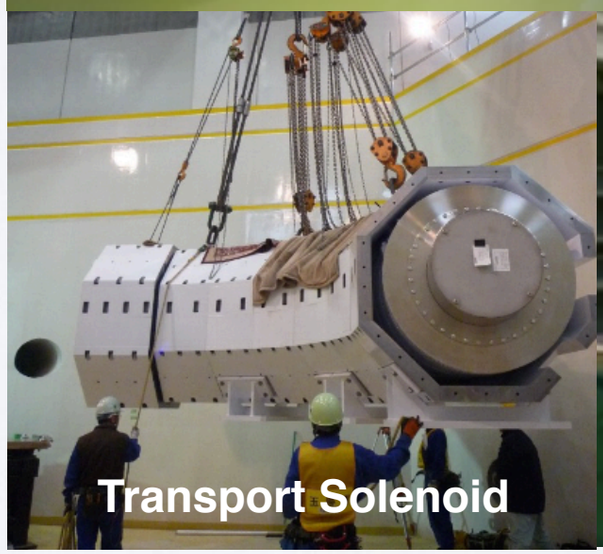




Magnets/Cryogenics

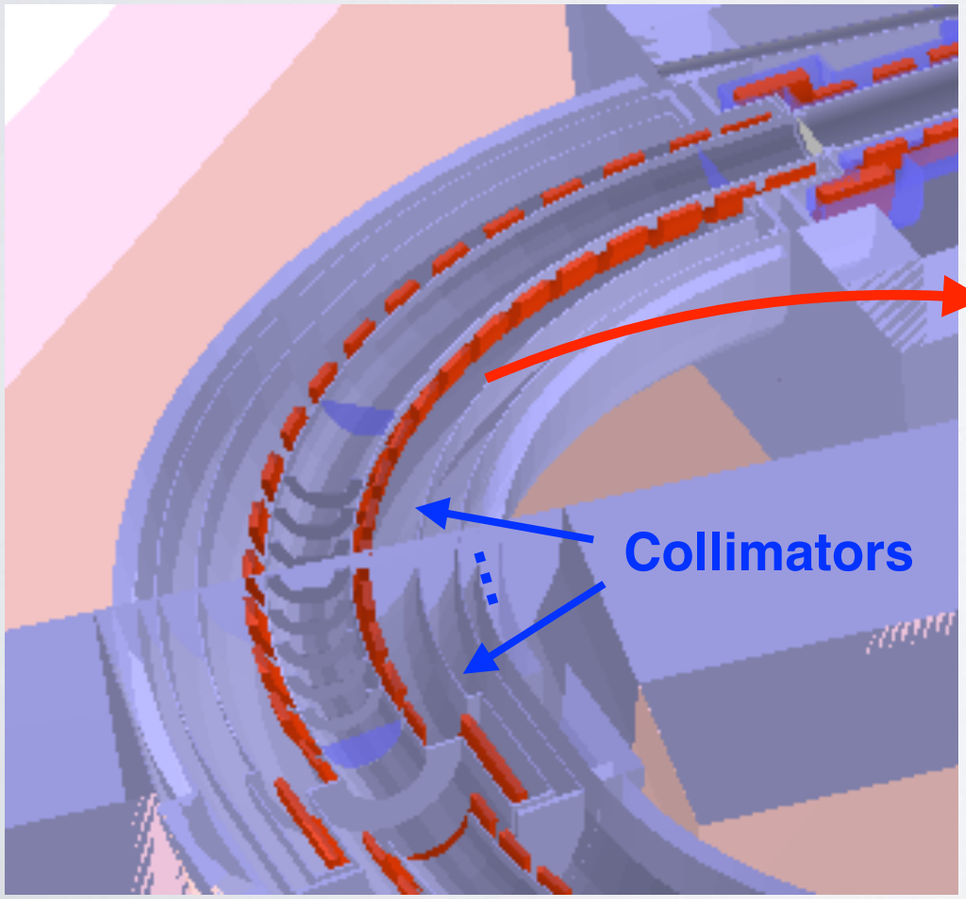
- **Pion capture solenoid**
  - Coil winding almost done
  - Mechanical design completed
- **Muon transport solenoid**
  - Completed, detailed tests are ongoing
- **Detector solenoid**
  - All 14 coils assembled as one
- **Cryogenics**
  - Engineering design is in preparation

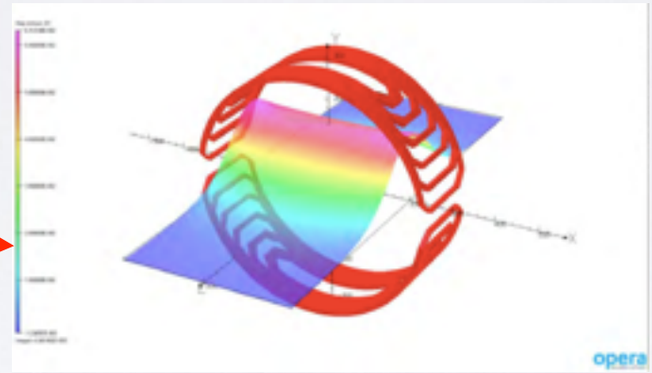




Muon Beam/Target

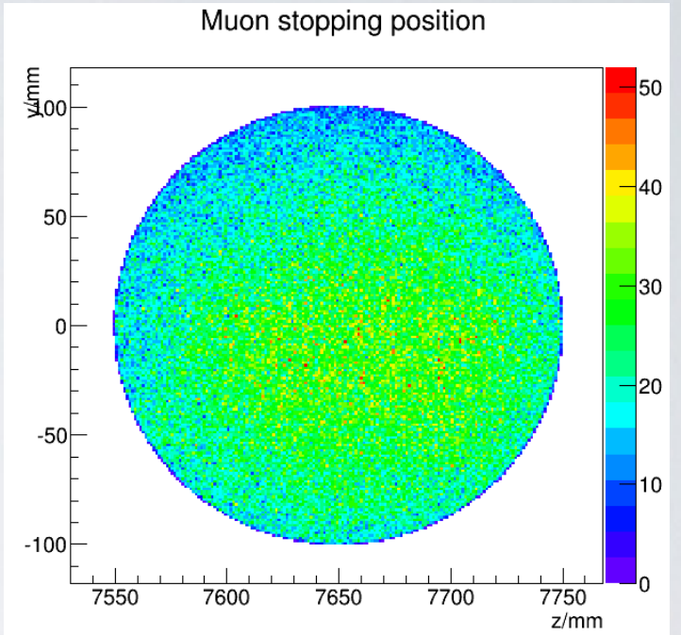
- Muon transported in a curved solenoid w/ a dipole field
  - Reduce pions which can produce high momentum secondaries
  - Momentum and charge selection
- Muons stopped inside the series of thin aluminum disks
  - Stopping rate for μ^-/π^- are ~5×10^{-4}/3×10^{-6} / POT



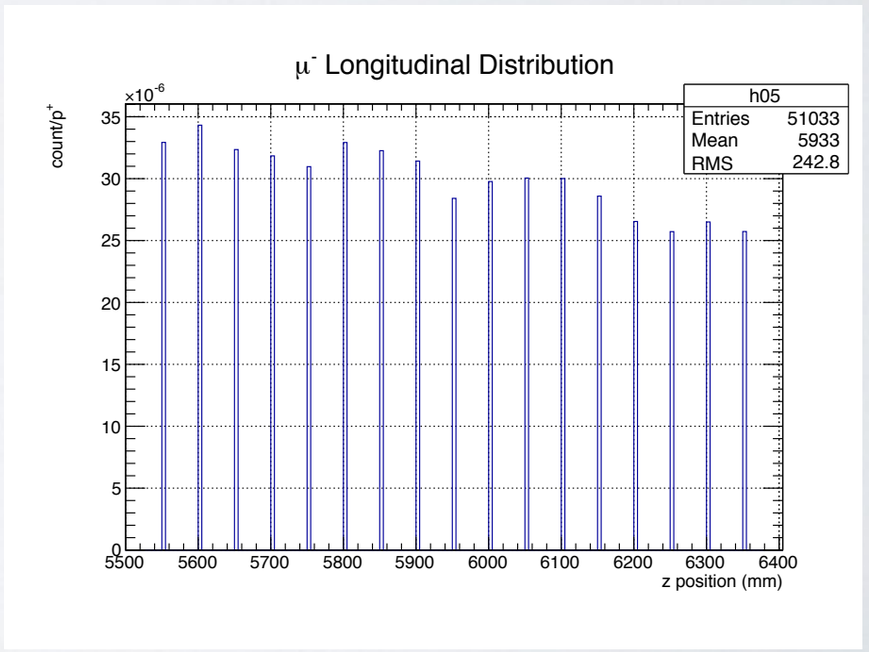


Saddle type coil is put outside of each solenoid coil to generate dipole field

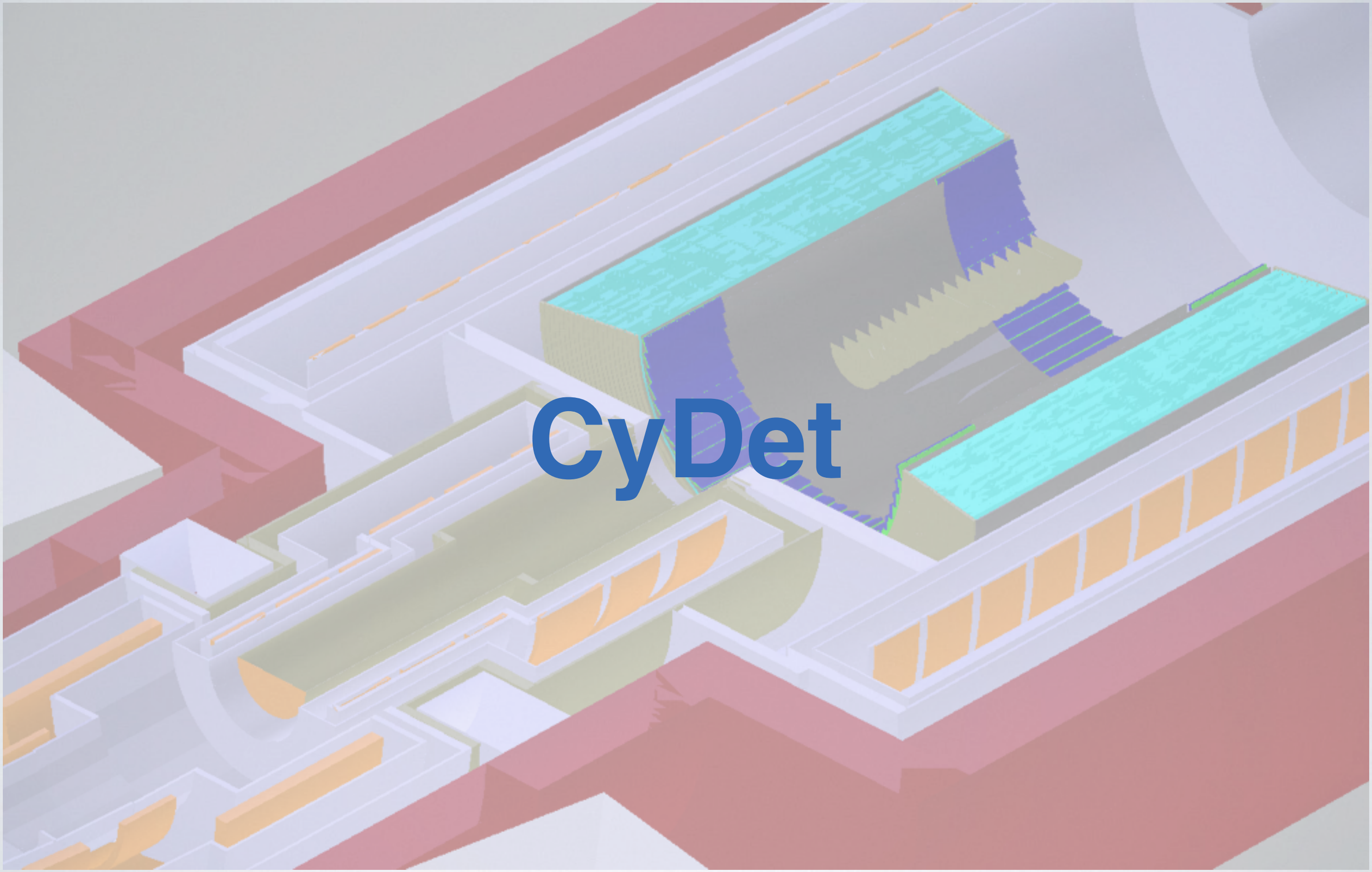
Keep the vertical position of low momentum muons



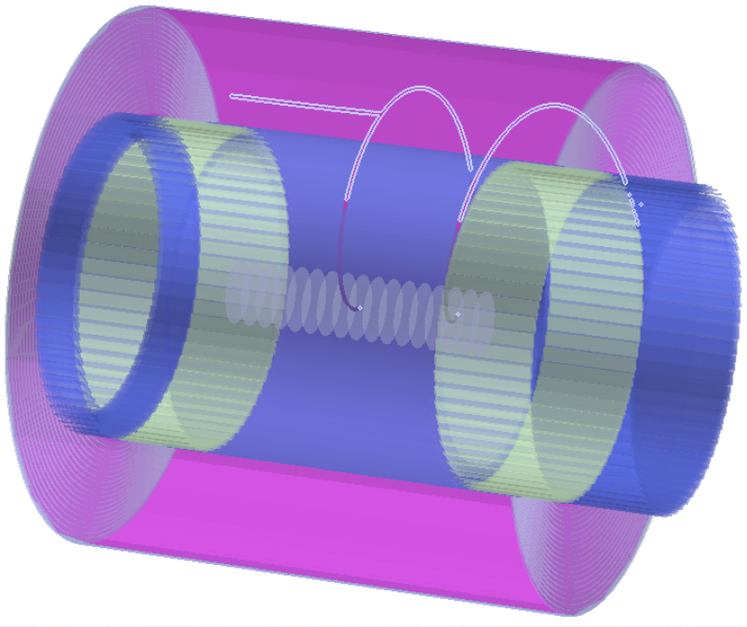
μ- stopping distribution projected on the target plane

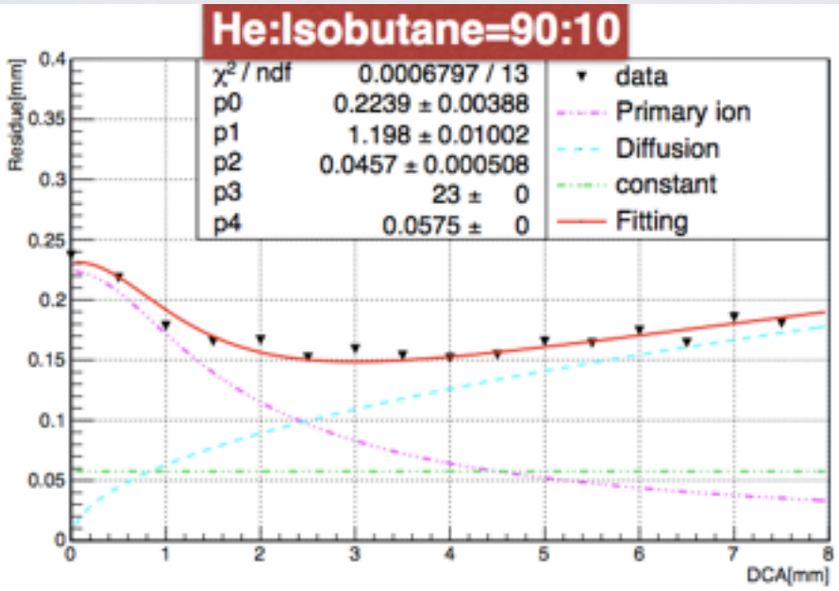


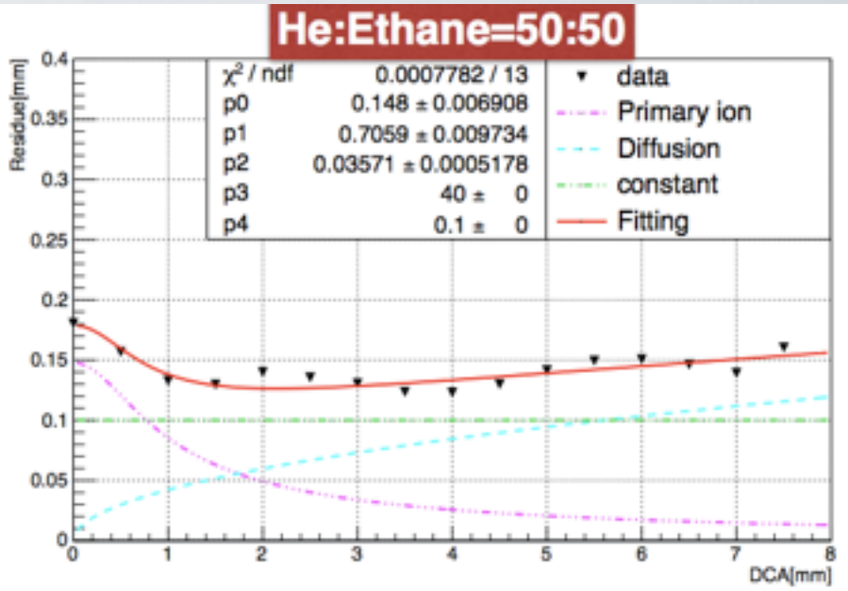
μ- stopping distribution along the beam axis


CyDet

CDC





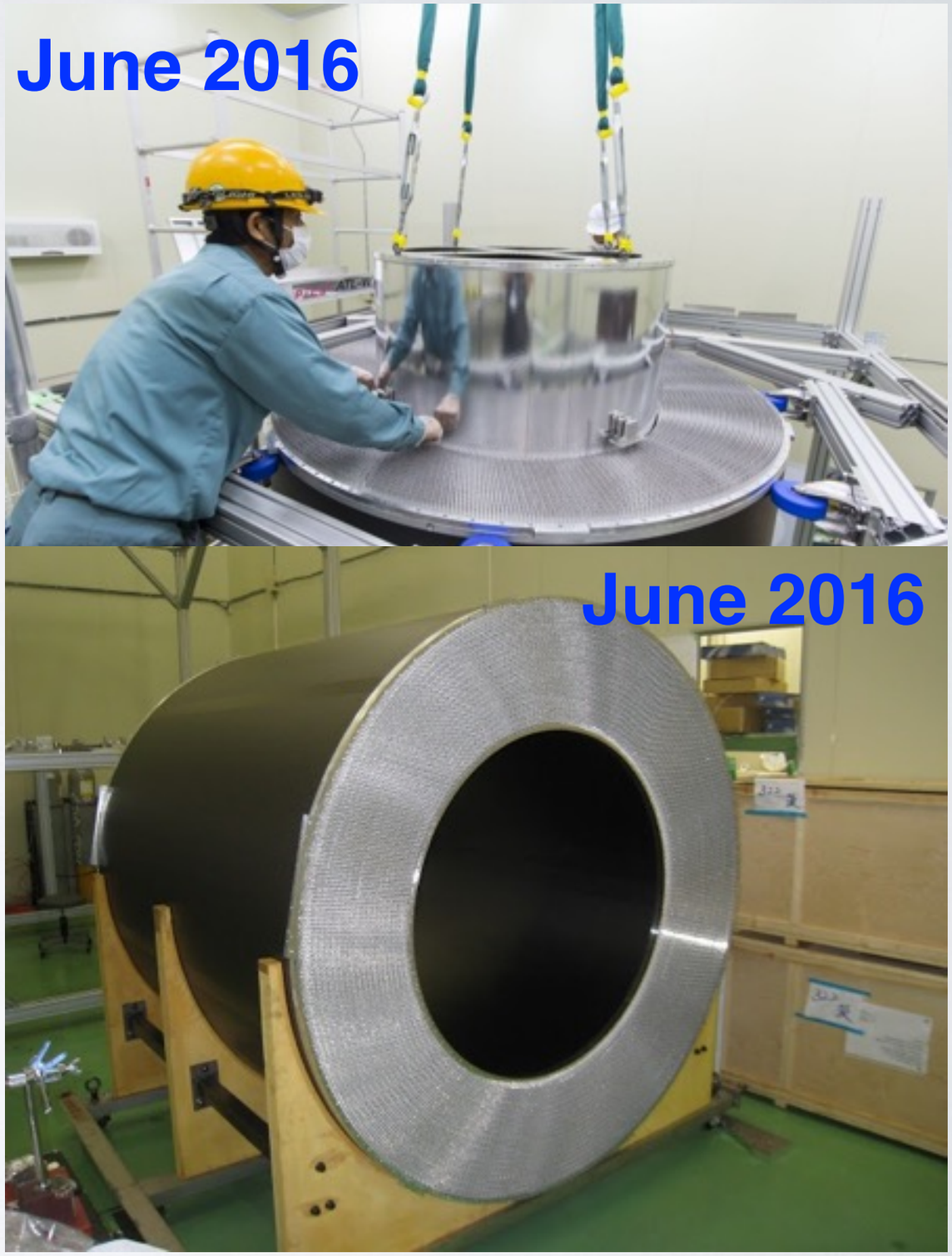


Position resolutions of CDC prototype obtained in the beam test @Spring-8

- **C**ylindrical **D**rift **C**hamber
- Main tracker for Phase-I physics measurement
  - All stereo wires enable to reconstruct 3D hit positions
  - 20 layers consists of ~5,000 sense wires + ~15,000 field wires
  - Gas mixture, He:iC_4H_{10}=90:10 or He:C_2H_6=50:50
- **Both gas mixtures show good performance**
  - Required momentum resolution, **σ_p ~ 200 keV/c** @p=105MeV/c, is achievable
- Mass production/test of readout boards done @IHEP

RECBE Board Mass Test @IHEP

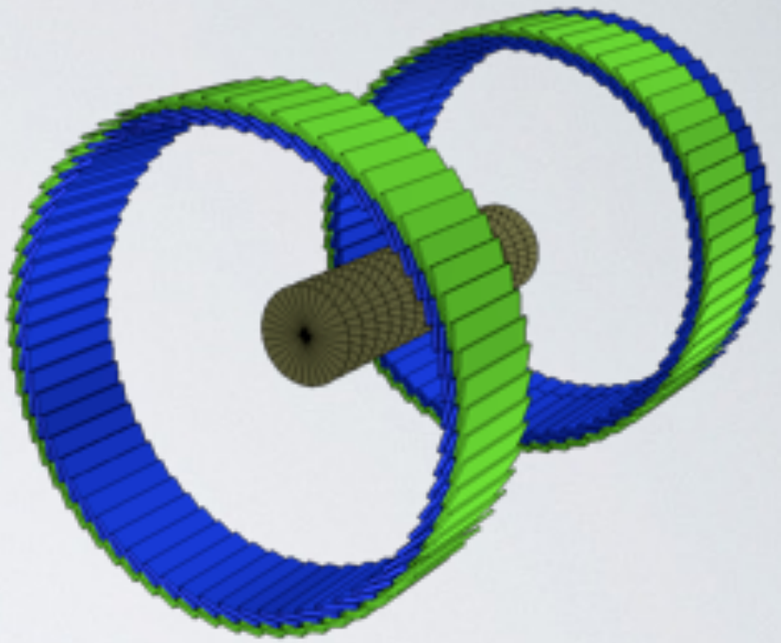
Detector Construction

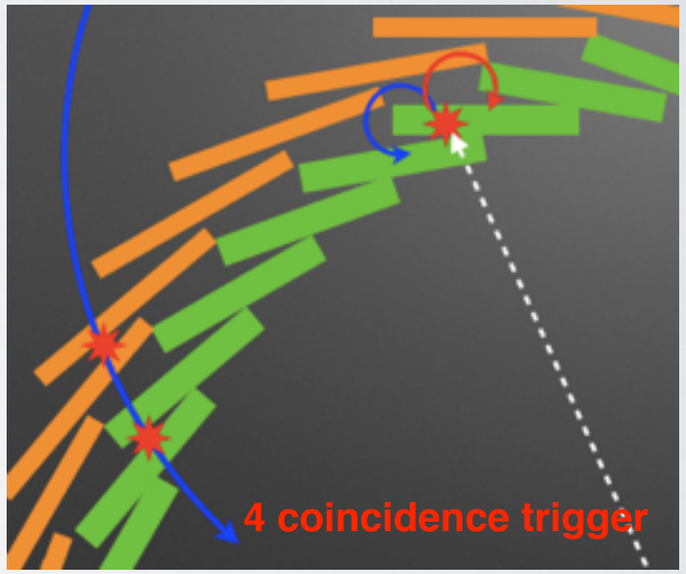


- **CDC construction completed this month**
  - All wires are fine
  - Inner wall installed
- Leak check has just begun
- Cosmic-ray test will be done soon

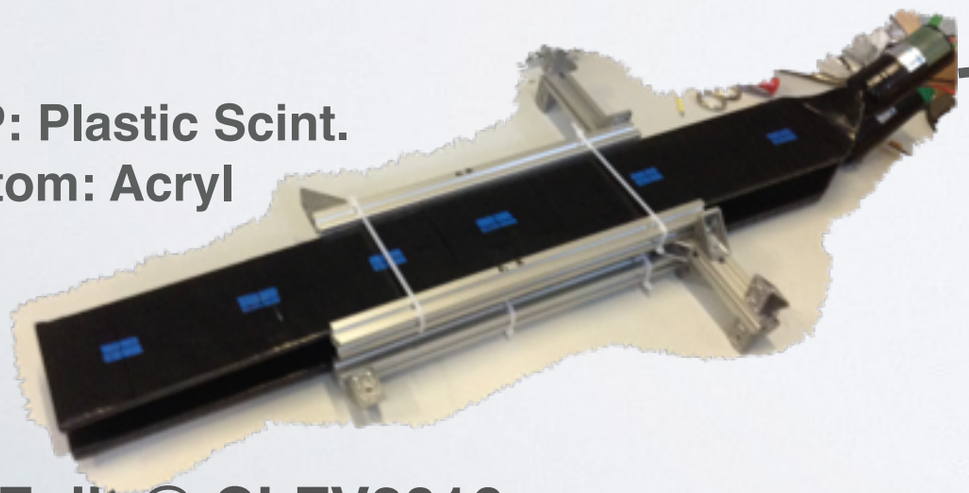
CTH

- **C**herenkov **T**rigger **H**odoscope
  - Each Module consists of an acrylic Cherenkov radiator and a plastic scintillator
  - 64 modules arranged both upstream/downstream sides
  - Require the 4 hits coincidence to suppress the accidental trigger due to γ rays
  - **Better than 1ns time resolution** obtained by using the prototype detector for 100MeV/c electrons
  - Preamplifier prototype produced and irradiation tests to be done



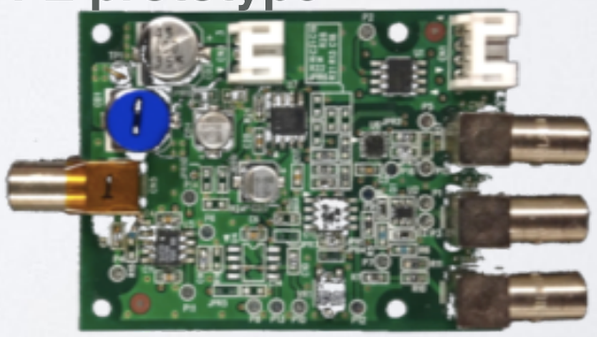


TOP: Plastic Scint.
Bottom: Acryl



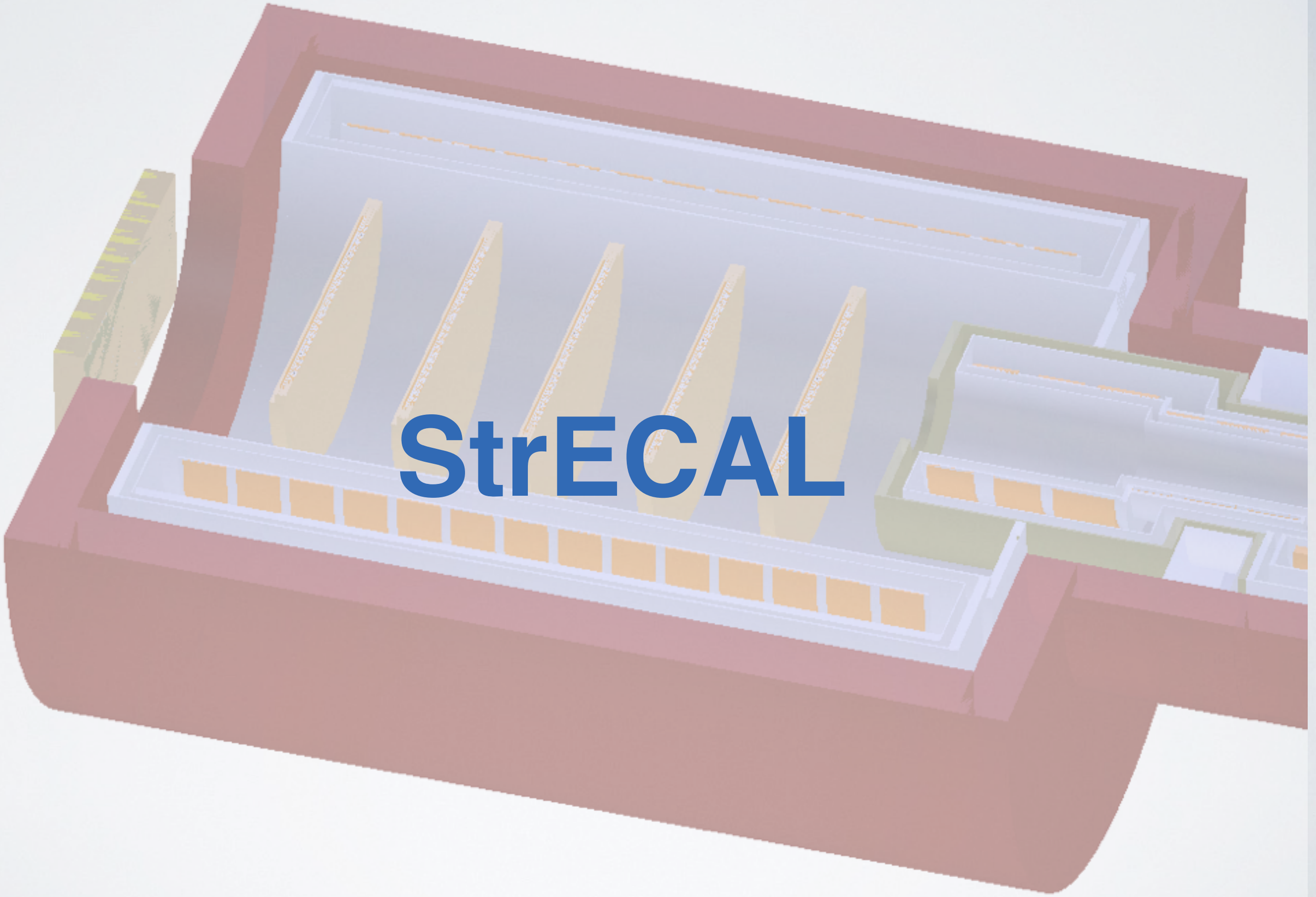
Fine mesh PMT

Analog FE prototype

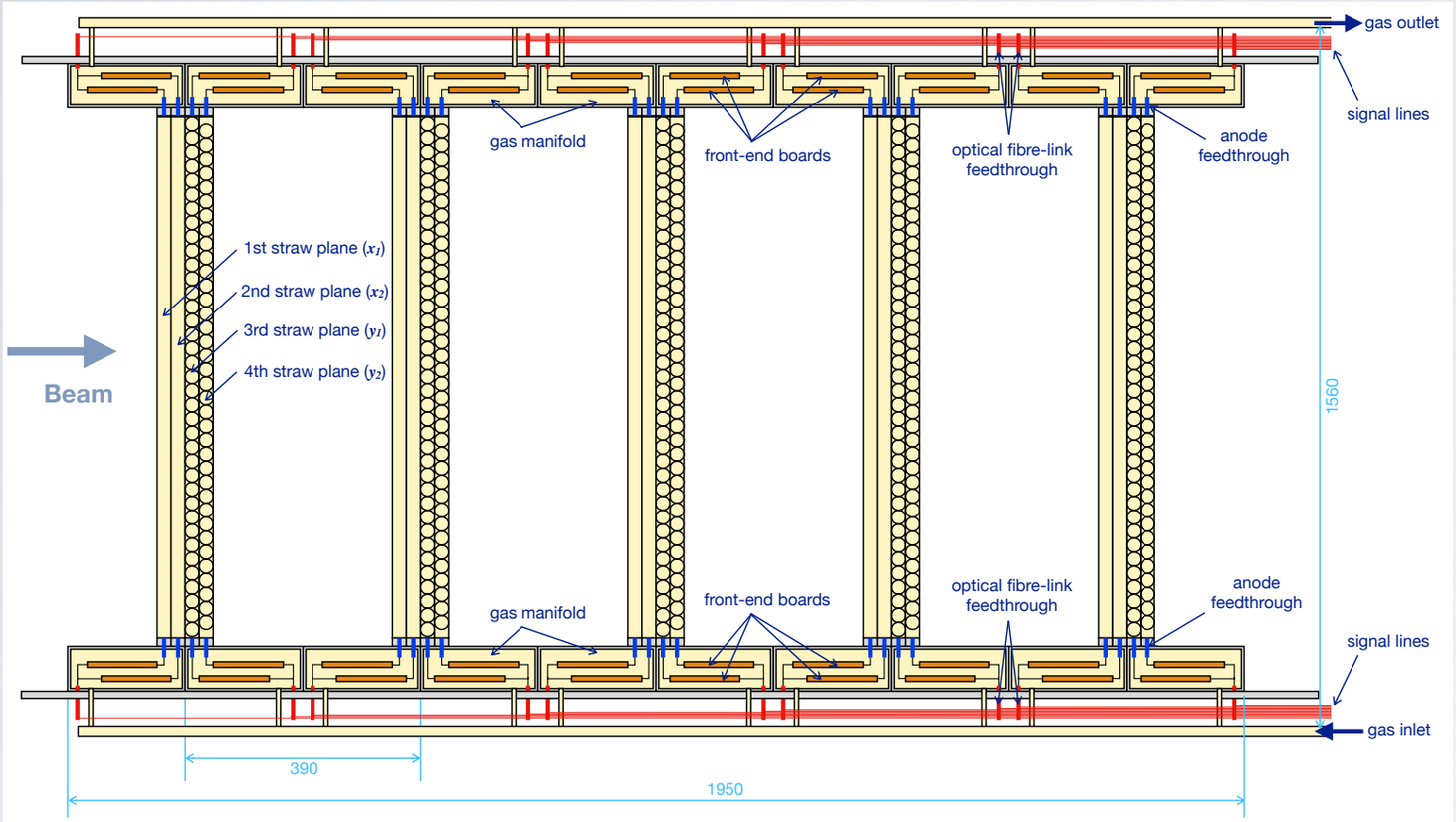


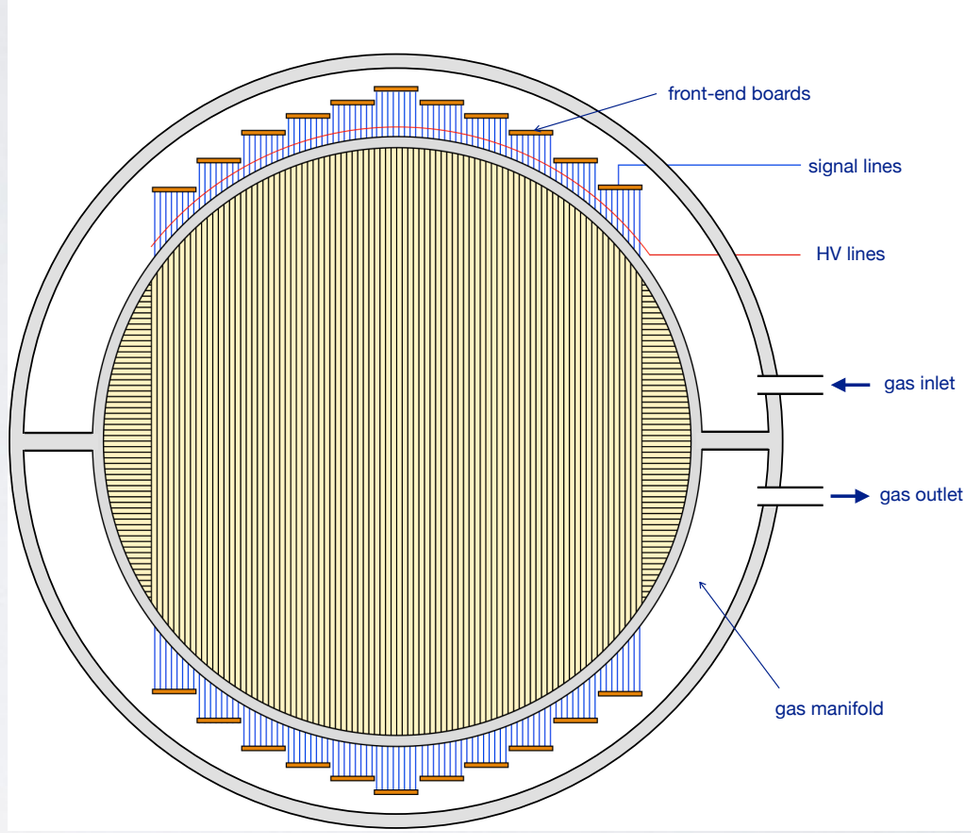
To digitizer

StrECAL



StrawTracker

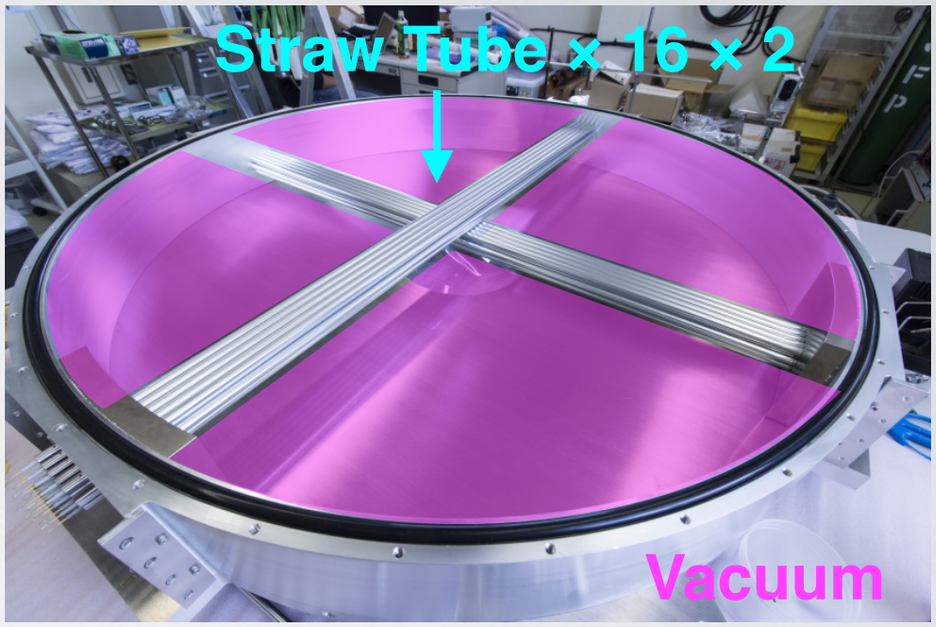


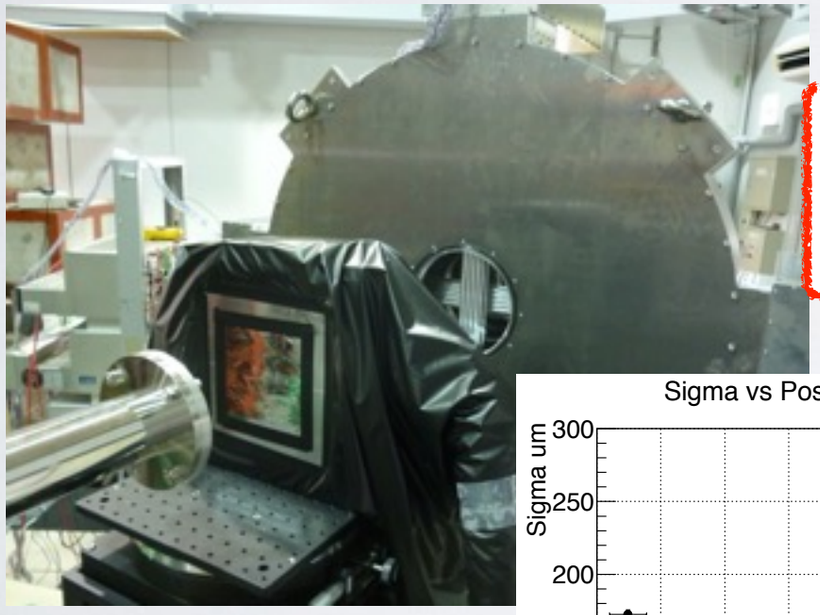


- **Straw** Tube **Tracker** consists of ~2500 straw tubes
  - Main tracker for Phase-I beam measurement / Phase-II physics measurement
  - **Operation in vacuum**
  - 20/12um thick, 9.8/5mmΦ straw tube for Phase-I/Phase-II
  - Gas mixture candidates: Ar:C_2H_6=50:50, Ar:CO_2=70:30
  - **Complete** the mass production of Phase-I straw tube

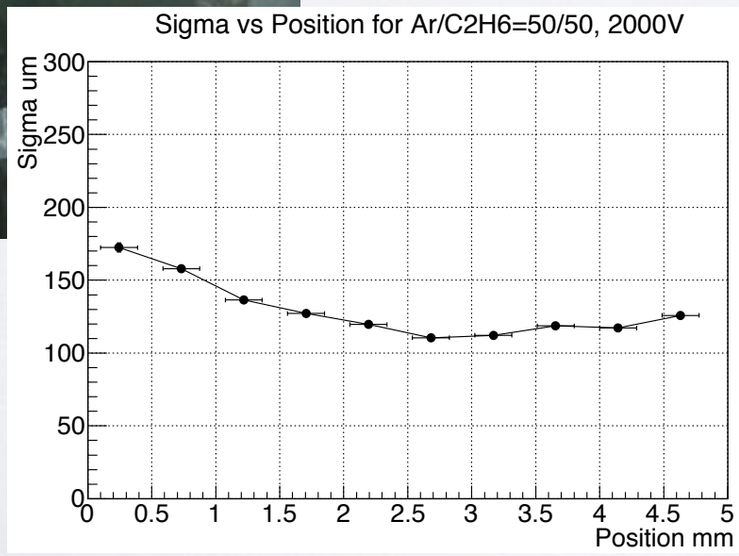
R&D and Construction Status

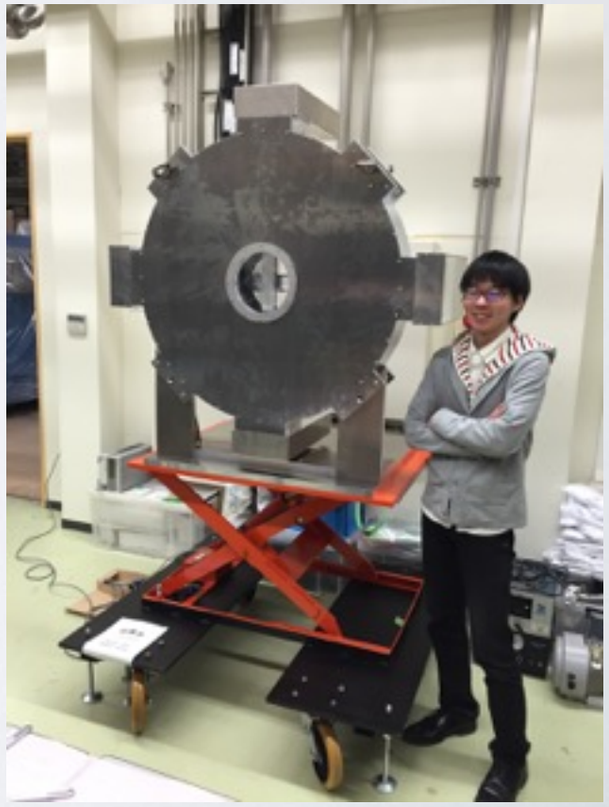
- Many tests carried out using full-scale prototype
  - Establish the construction procedure
  - Evaluate out-gas rate of straw tubes
    - No leak, no significant out-gas
  - Beam test w/ 105MeV/c electron was done
    - **σ_x~150um obtained → σ_p~180keV/c**
  - **Operation in vacuum performed in success**
- **All Phase-I straw tubes have been built already**



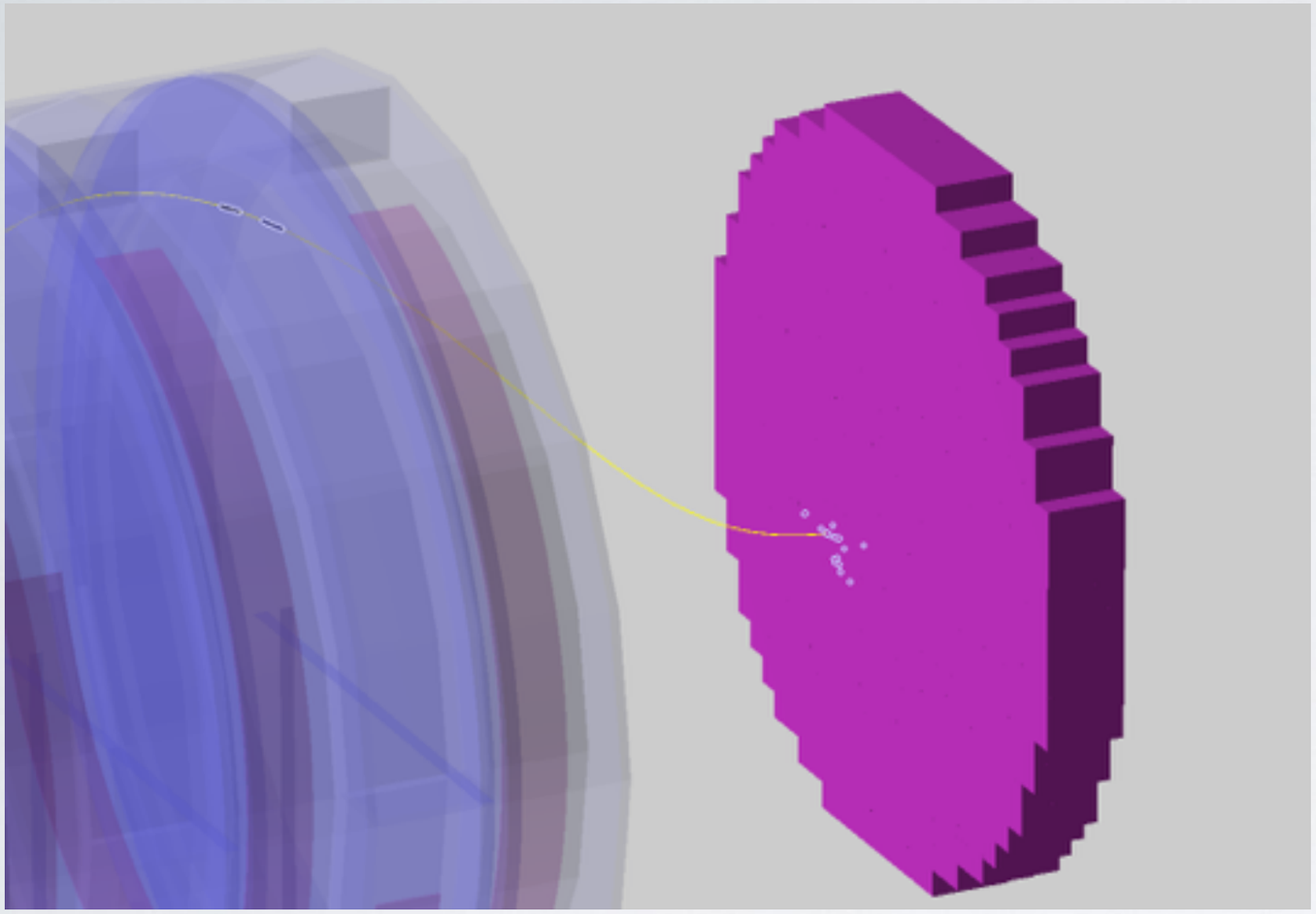


Less than 200um σ_x everywhere



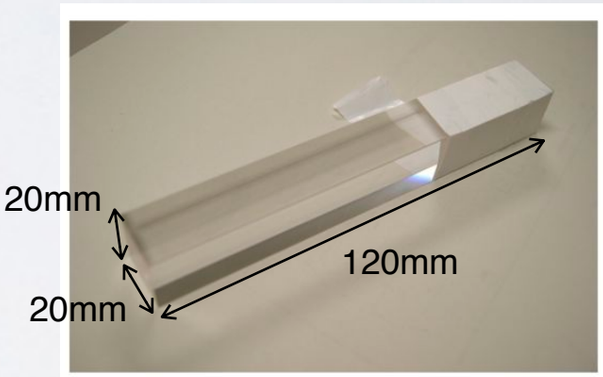


ECAL



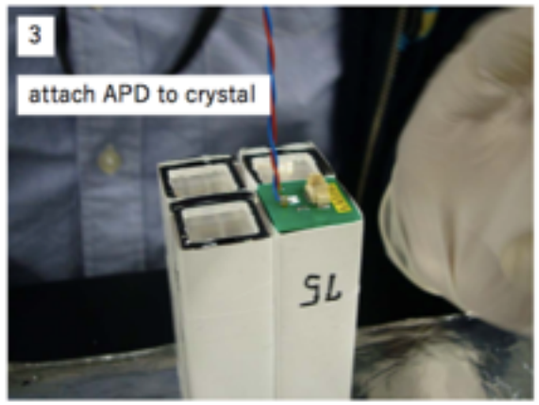
	NaI(Tl)	GSO	LYSO
Density, g/cm^3	3.67	6.71	7.1
Att. length, cm	2.6	1.38	1.12
Decay const., ns	230	30-60	41
Max emission, nm	415	430	420
Relative LY	100	20	70-80

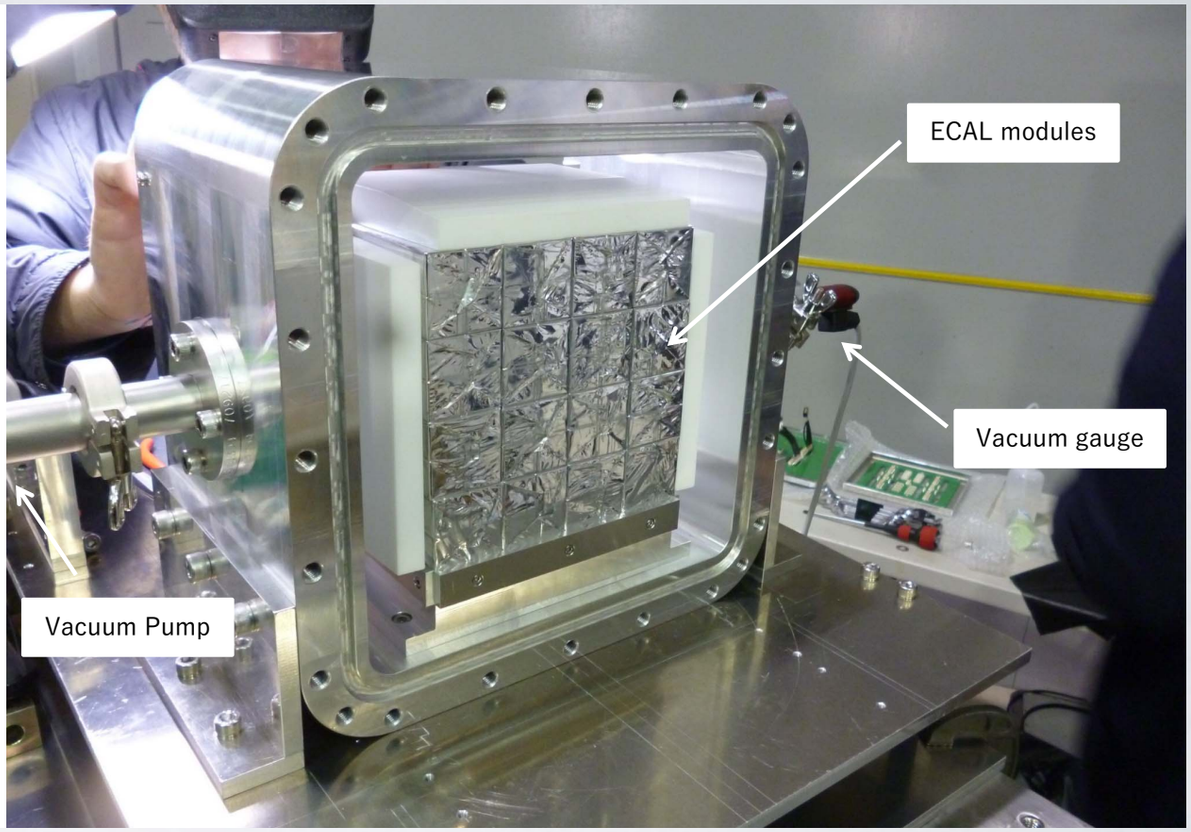
Comparisons of scintillator characteristics



- ECAL is an array of ~2,000 scintillator crystals to cover ~1m of radius
  - Choose **LYSO** because of the higher light yield and faster time response than GSO
  - Use in both Phase-I & Phase-II
  - **Measure the energy deposit** and **trigger the event**
  - 10mm×10mm APD sensor attached to the back of each LYSO crystal
  - Crystals and APDs inside vacuum

R&D Status





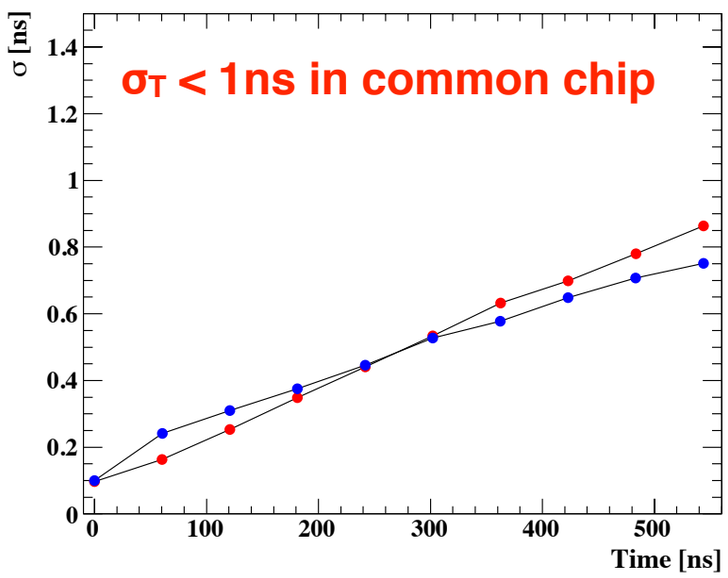
- Single crystal optimizations
  - APD: 5×5mm^2 → 10×10mm^2, ×3 photon yield
  - Wrapping: Teflon+Al-mylar → ESR+Teflon, ×1.3 photon yield

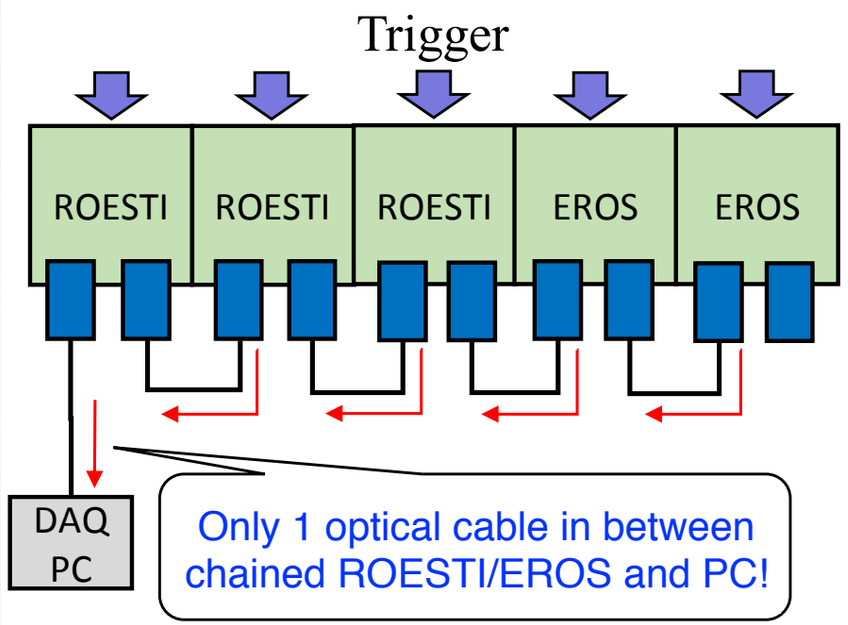
} **×4 larger**

- Vacuum test using 8×8 prototype detector newly manufactured
  - **Reach ~1Pa vacuum level**
- Two candidates
  - Saint-Gobain and OXIDE, performance comparison ongoing

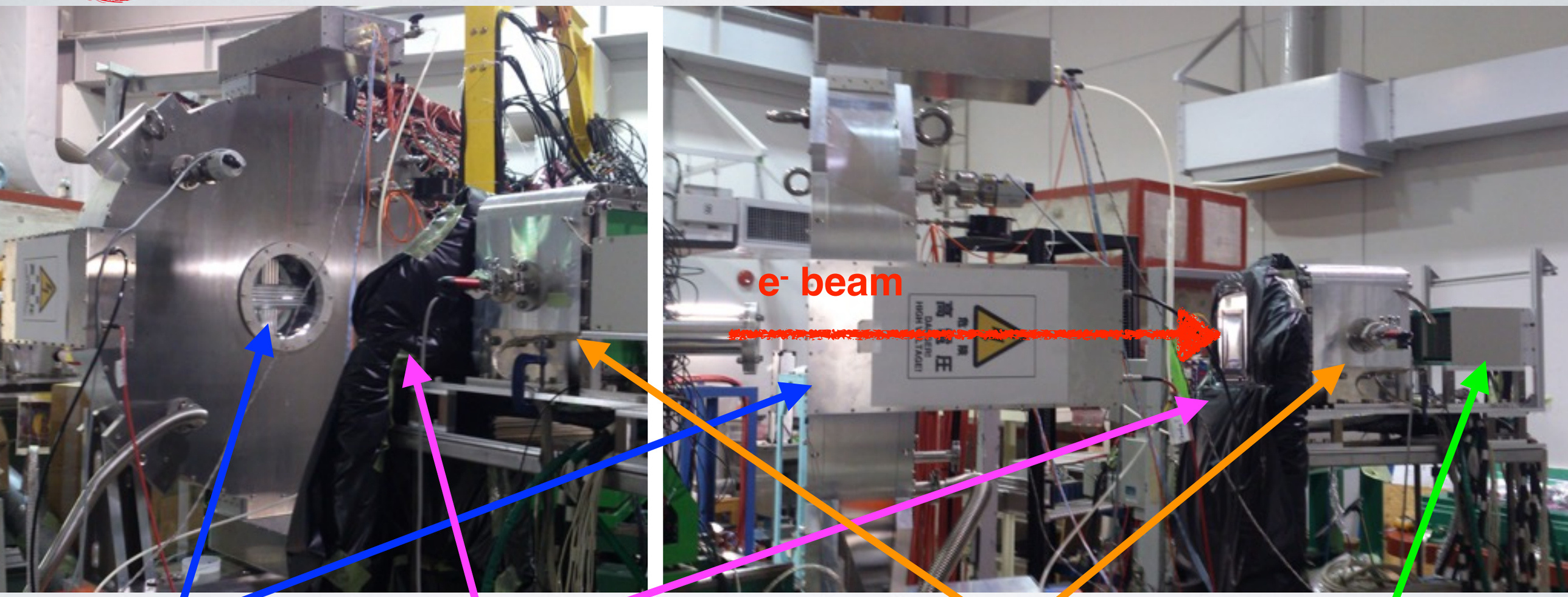
Readout for StrawECAL

- New waveform digitizer boards being developed based on DRS4
  - **ROESTI**: (**R**ead **O**ut **E**lectronics for **S**traw **T**ube **I**nstruments)
  - **EROS**: (**E**cal **R**ead **O**ut **S**ystem)
  - ROESTI/EROS are almost same except for the analog input
- <1ns σ_T obtained using ROESTI v3 by applying calibration
- **"Real" daisy chain readout developed recently**





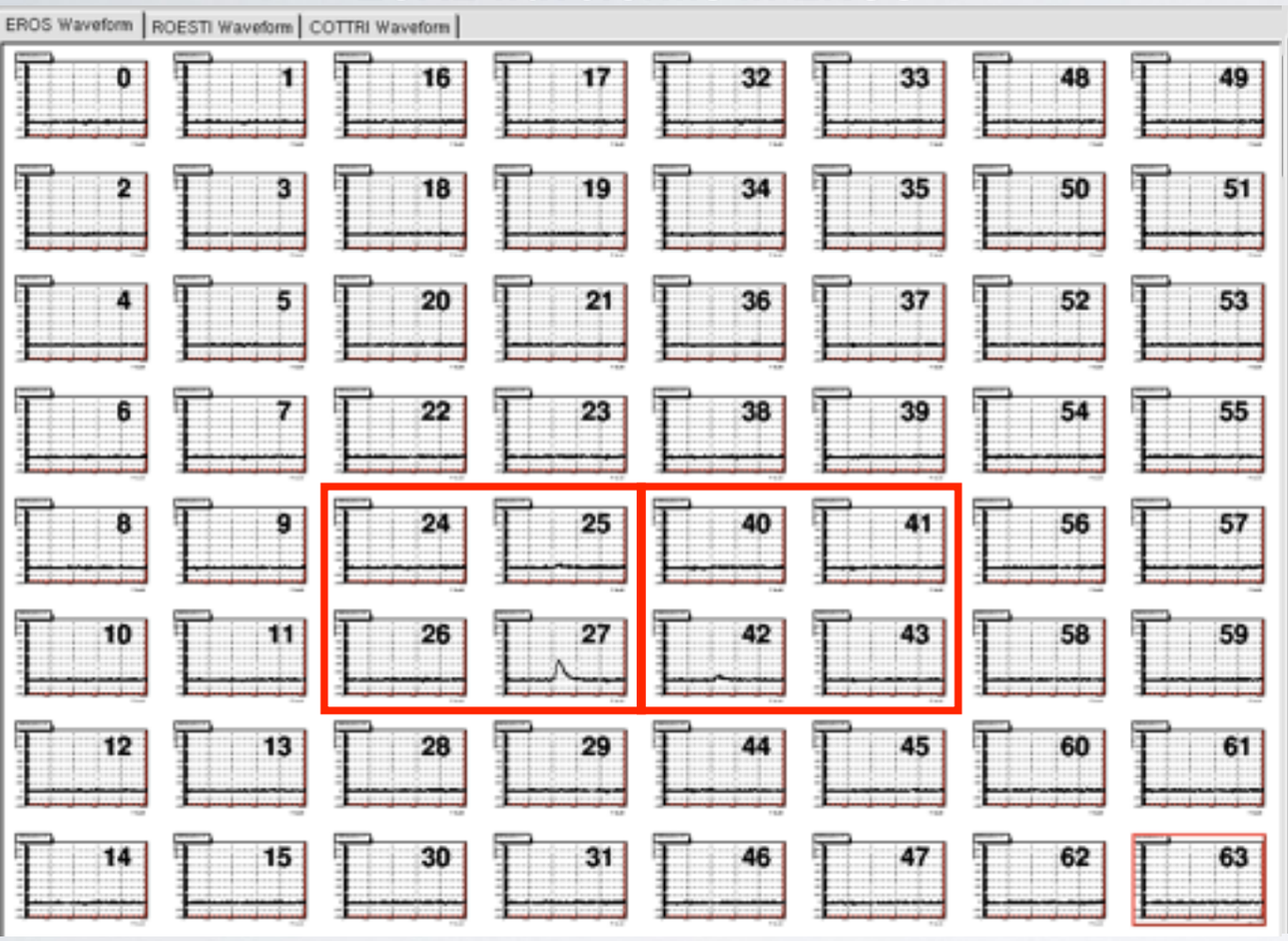
Beam Test @Tohoku



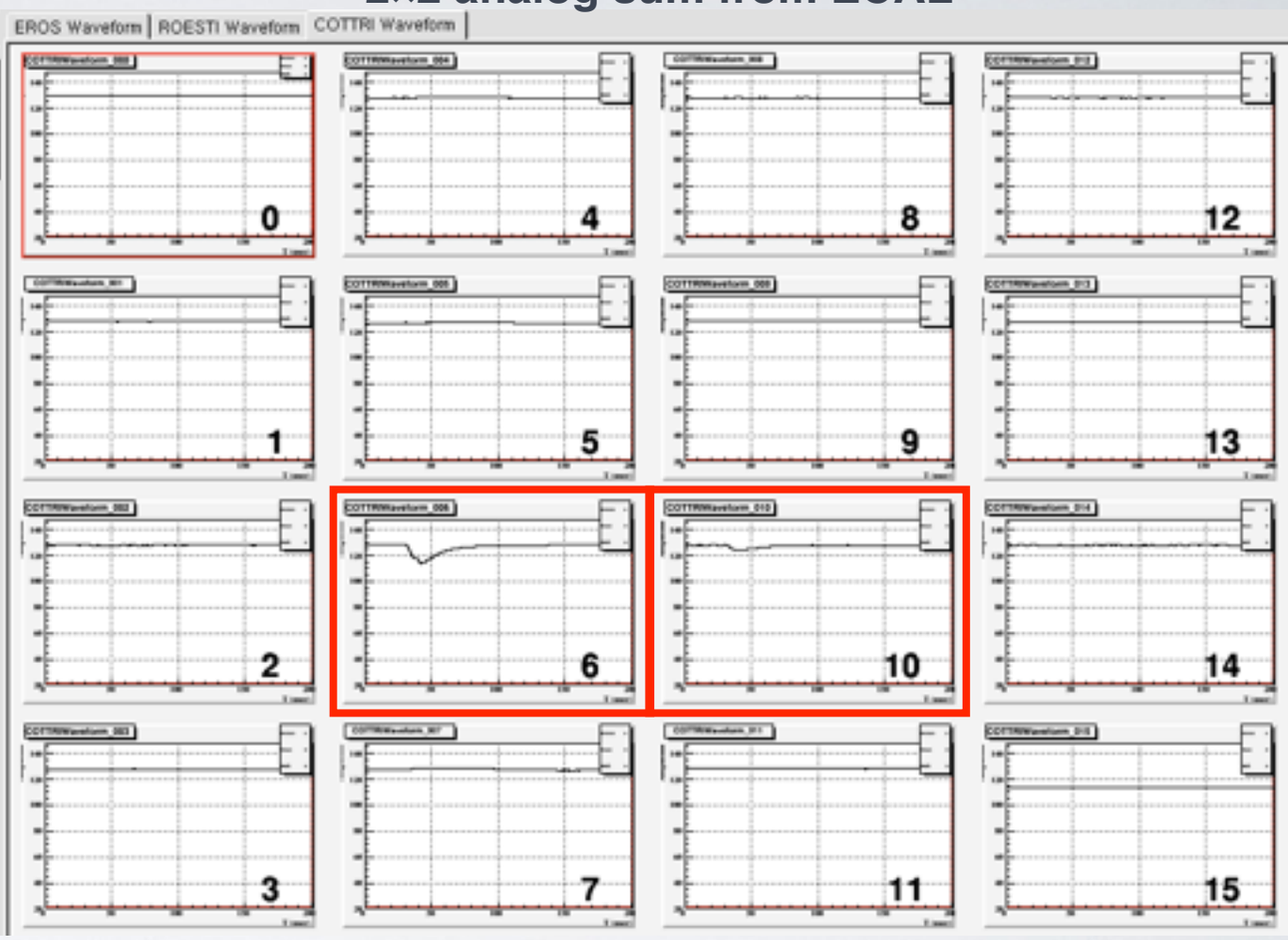
- **1st beam test for Straw+ECAL combined system** was performed in March 2016
- ROESTI/EROS prototypes are used as the readout
- Test the ECAL self-trigger using new preamp and front-end trigger boards
- Crystal comparison (Saint-Gobain & OXIDE)

Beam Test Results

ECAL waveforms in EROS



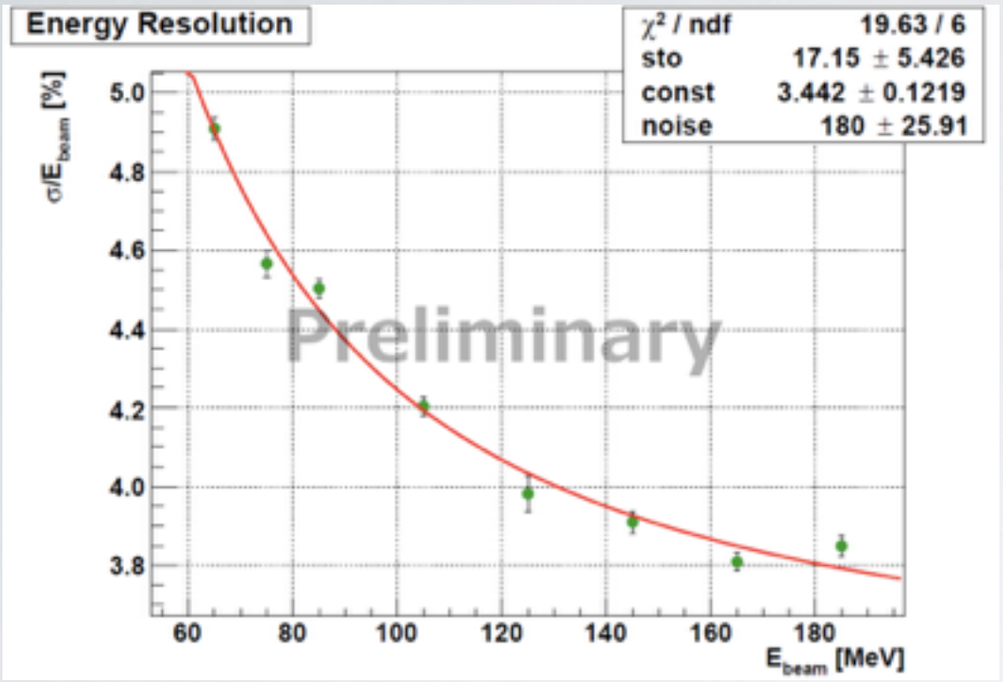
2×2 analog sum from ECAL

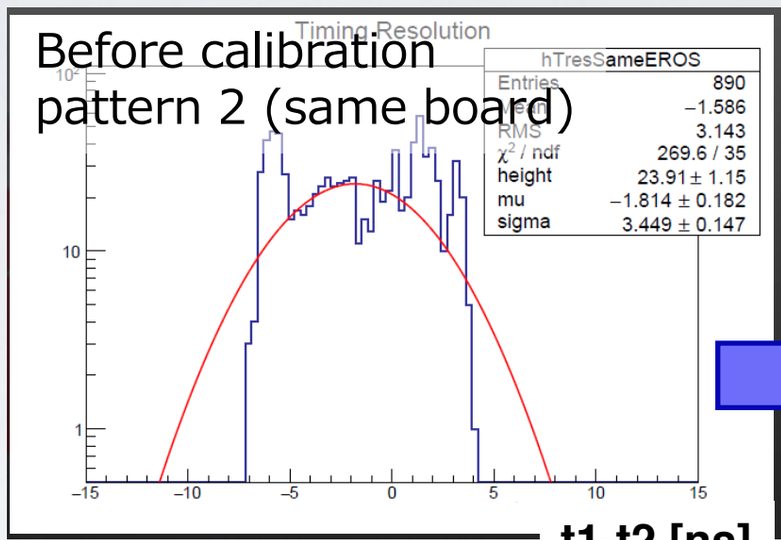


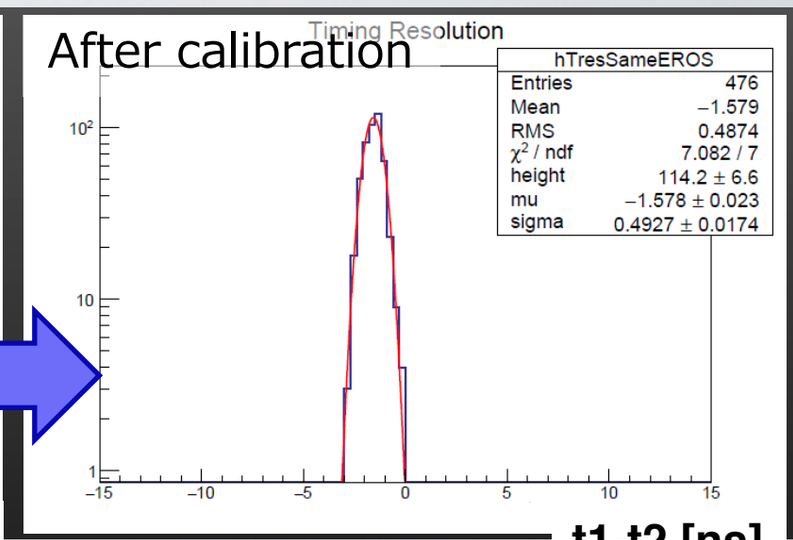
- **Success to take data w/ ECAL self-trigger** using COTTRI*+FCT
- Analysis ongoing
- We also took data for Straw w/ ECAL self-trigger mode successfully

*COTTRI is a front-end trigger system for CyDet and backup solution for StrawECAL

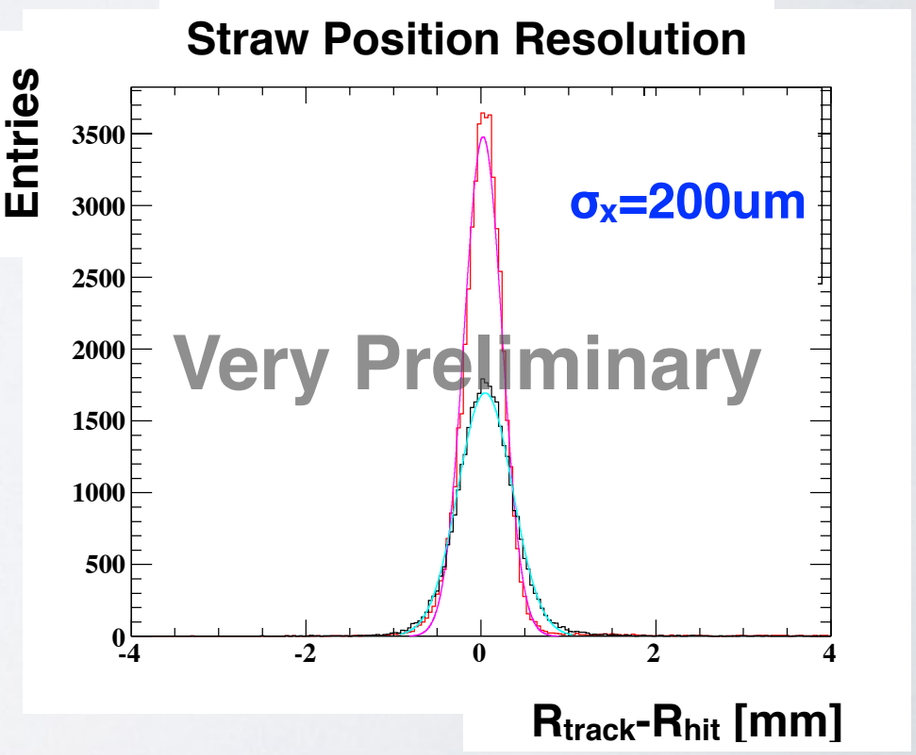
Beam Test Results

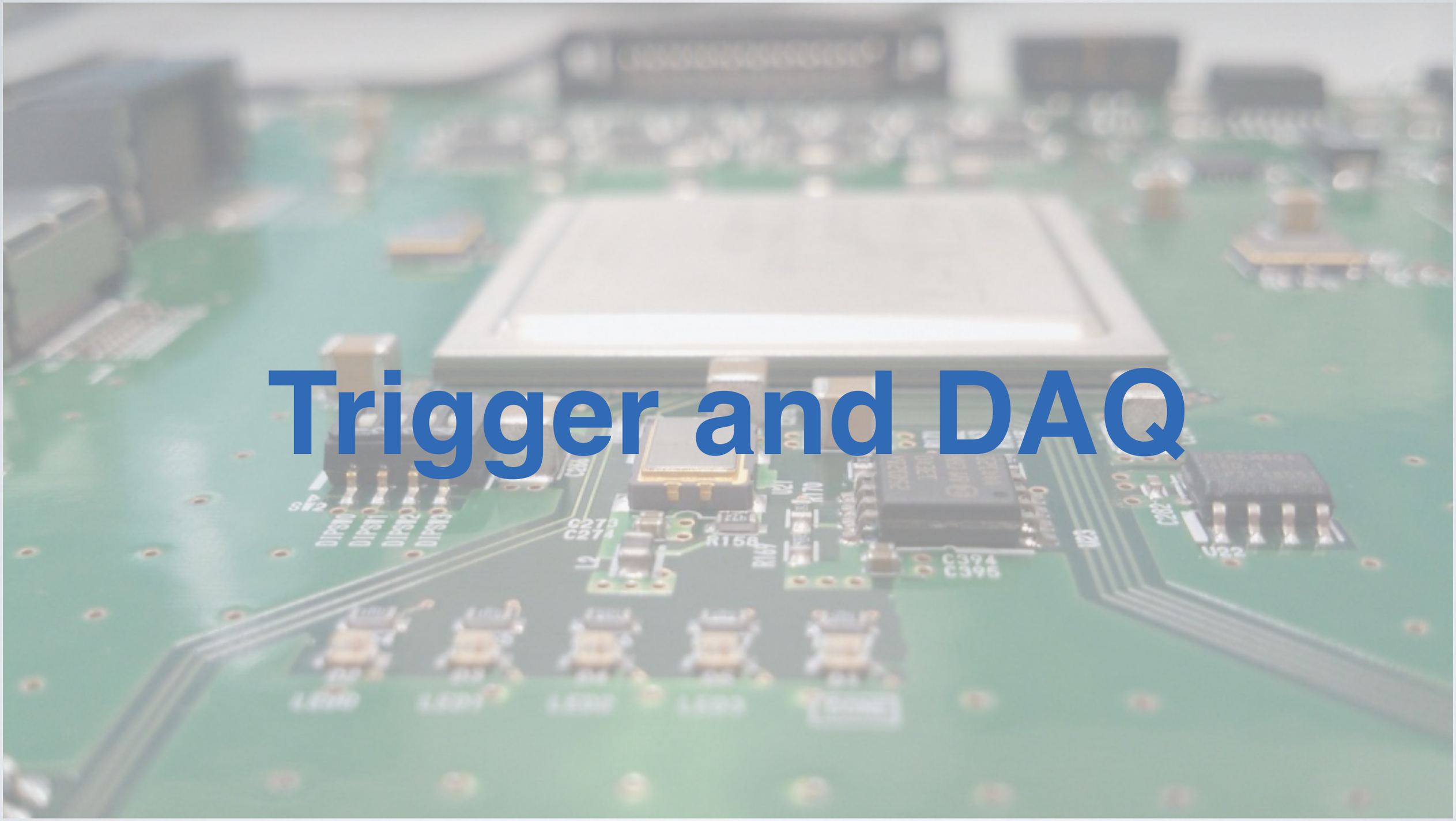






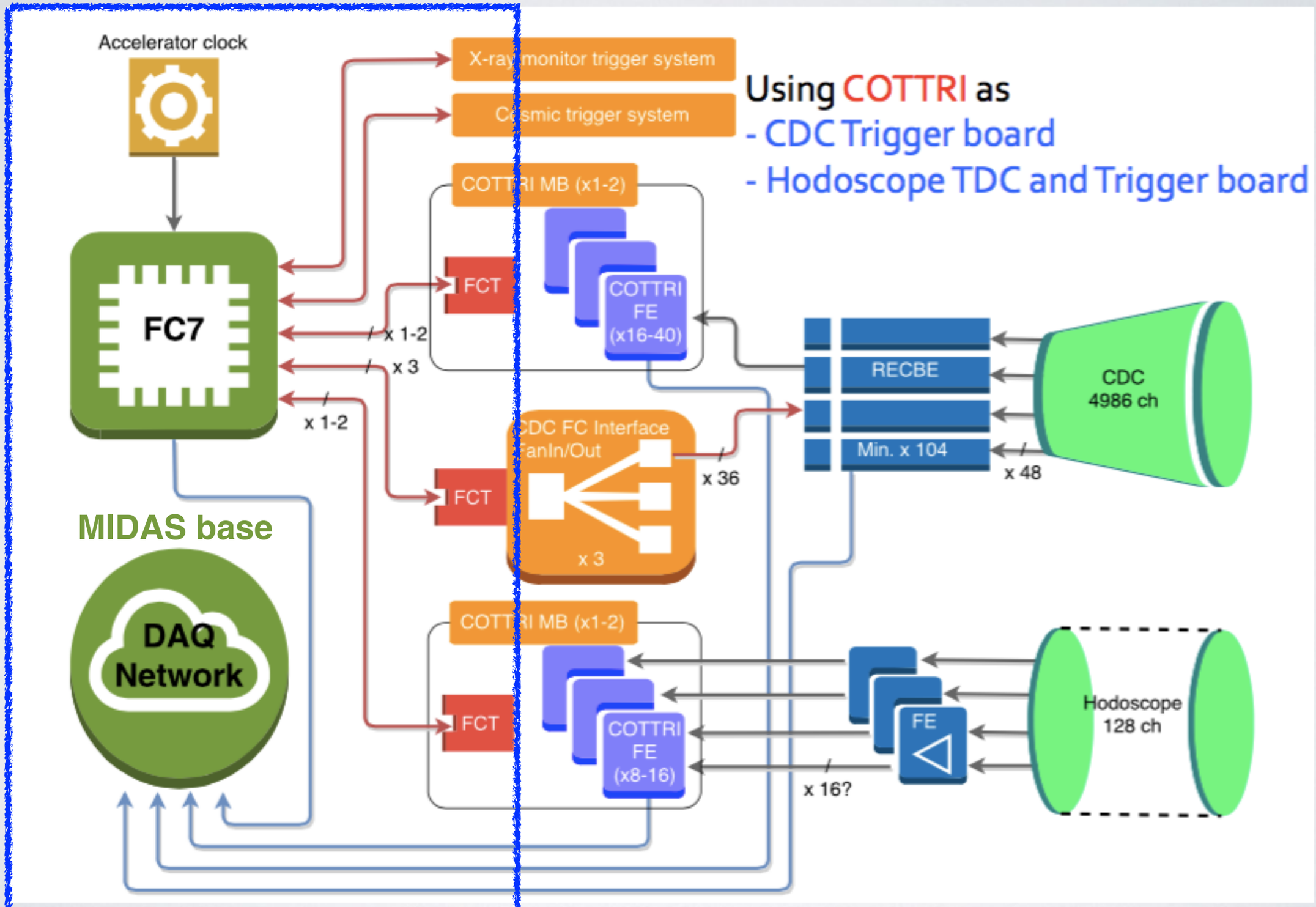
- Demonstration of MIDAS DAQ with ROESTI & EROS successfully done
- **4.2%** of σ/E obtained for ECAL (preliminary)
- ECAL σ_T calculated to be **0.19, 0.35 and 0.42ns** for same chip, same board and diff. board, respectively (preliminary)
- StrawTracker shows 200um σ_x including track length uncertainty





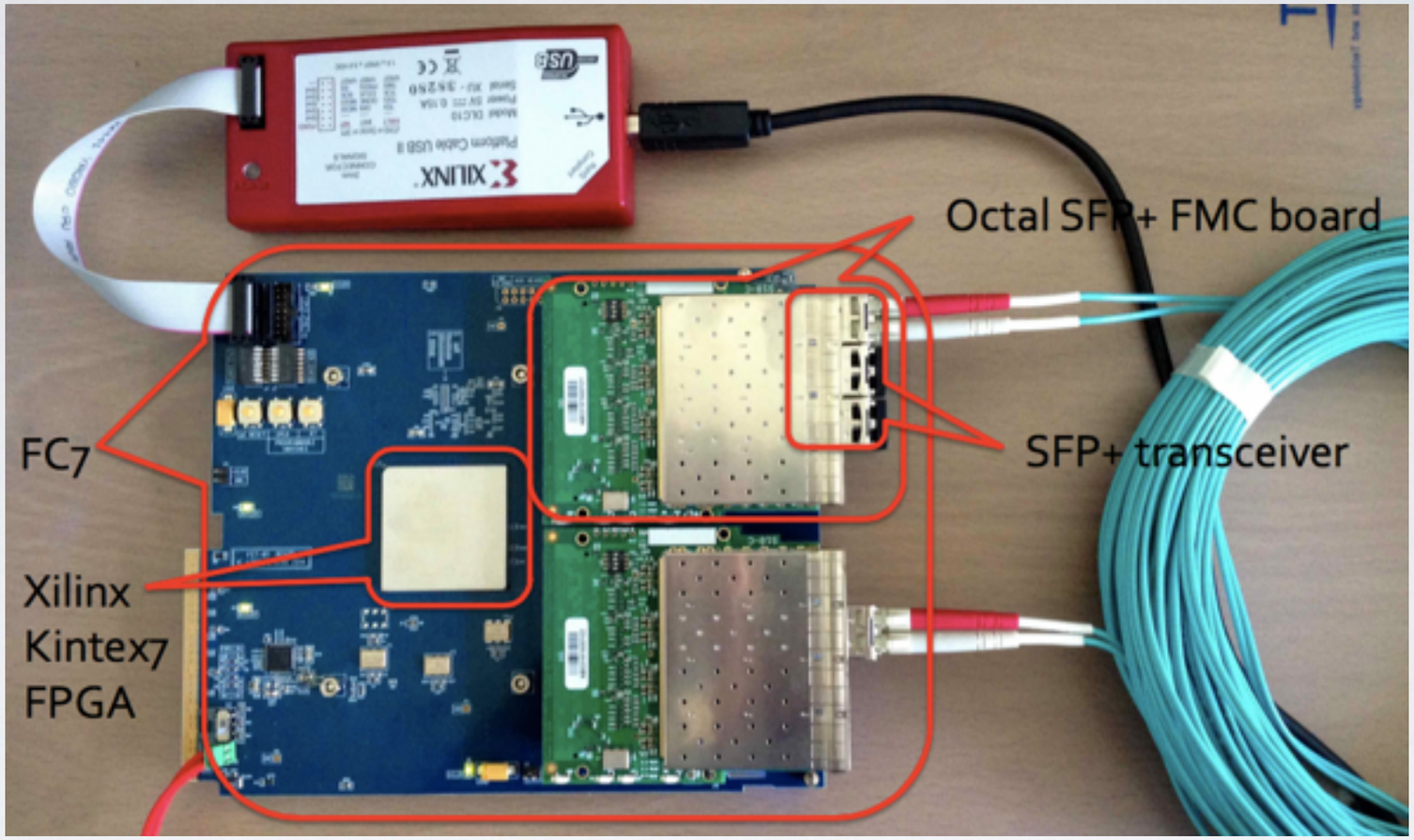
Trigger and DAQ

Trigger Overview



Common for CyDet and StrawECAL

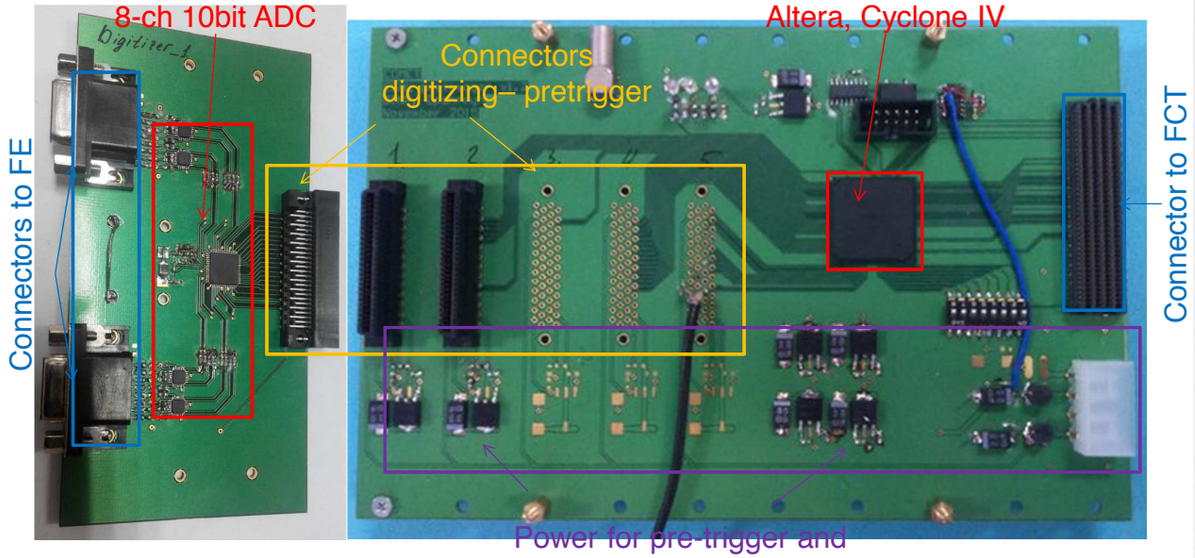
FCT



- **F**ast **C**ontrol and **T**iming system
  - Central **FC7** controls trigger signals and provides 40MHz common clock
  - Communications between FC7 and each readout/trigger board handled by the intermediating board, **FCT**
  - FC7-FCT bi-directional link established recently
    - **125ns** latency for oneway is obtained, should be short enough
  - More FC7 will be purchased for COMET in this year

Frontend Trigger System

Prototype v.2 of the Pre-trigger board and digitizing board



Leonid Epshteyn, Novosibirsk group

19/05/16

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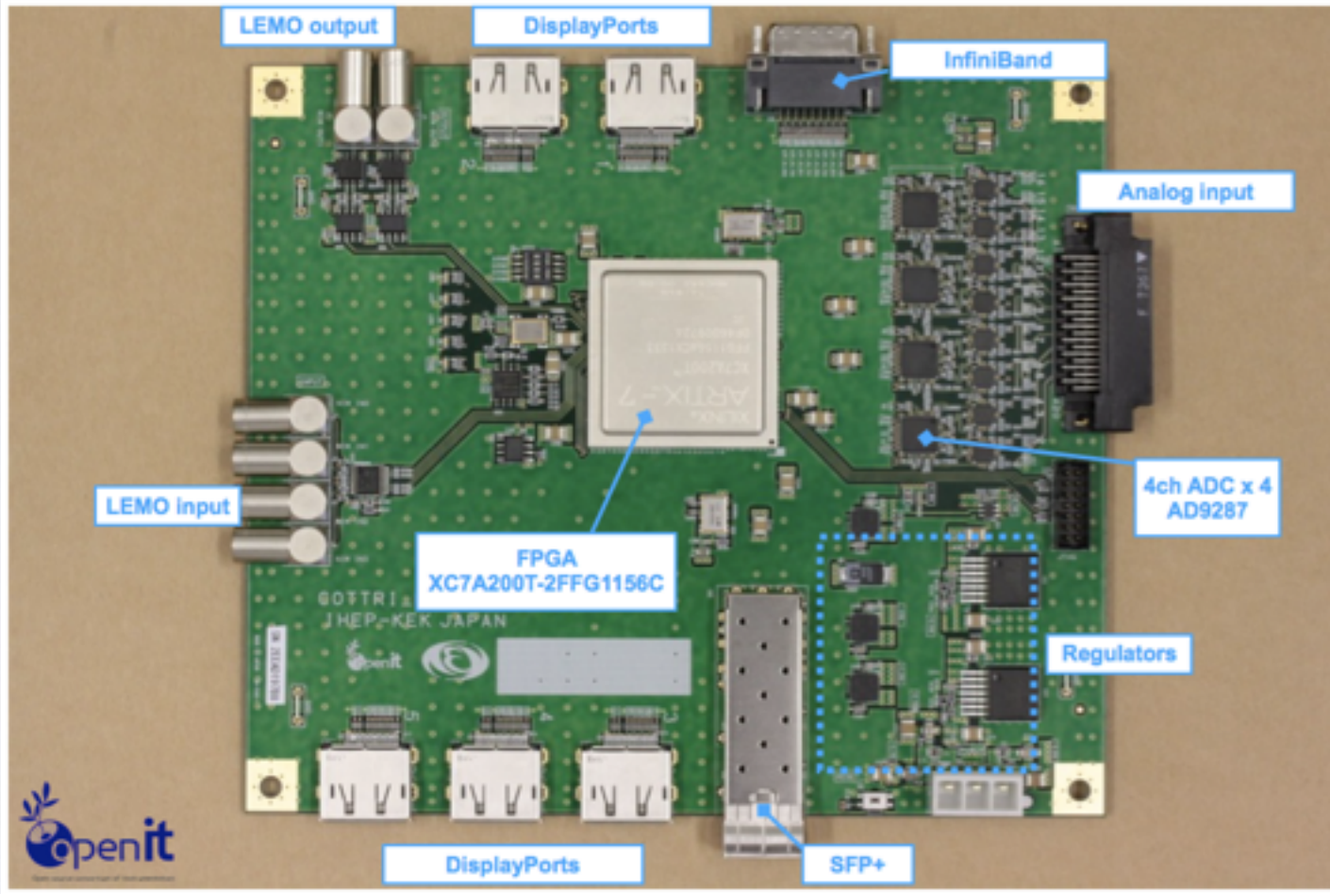
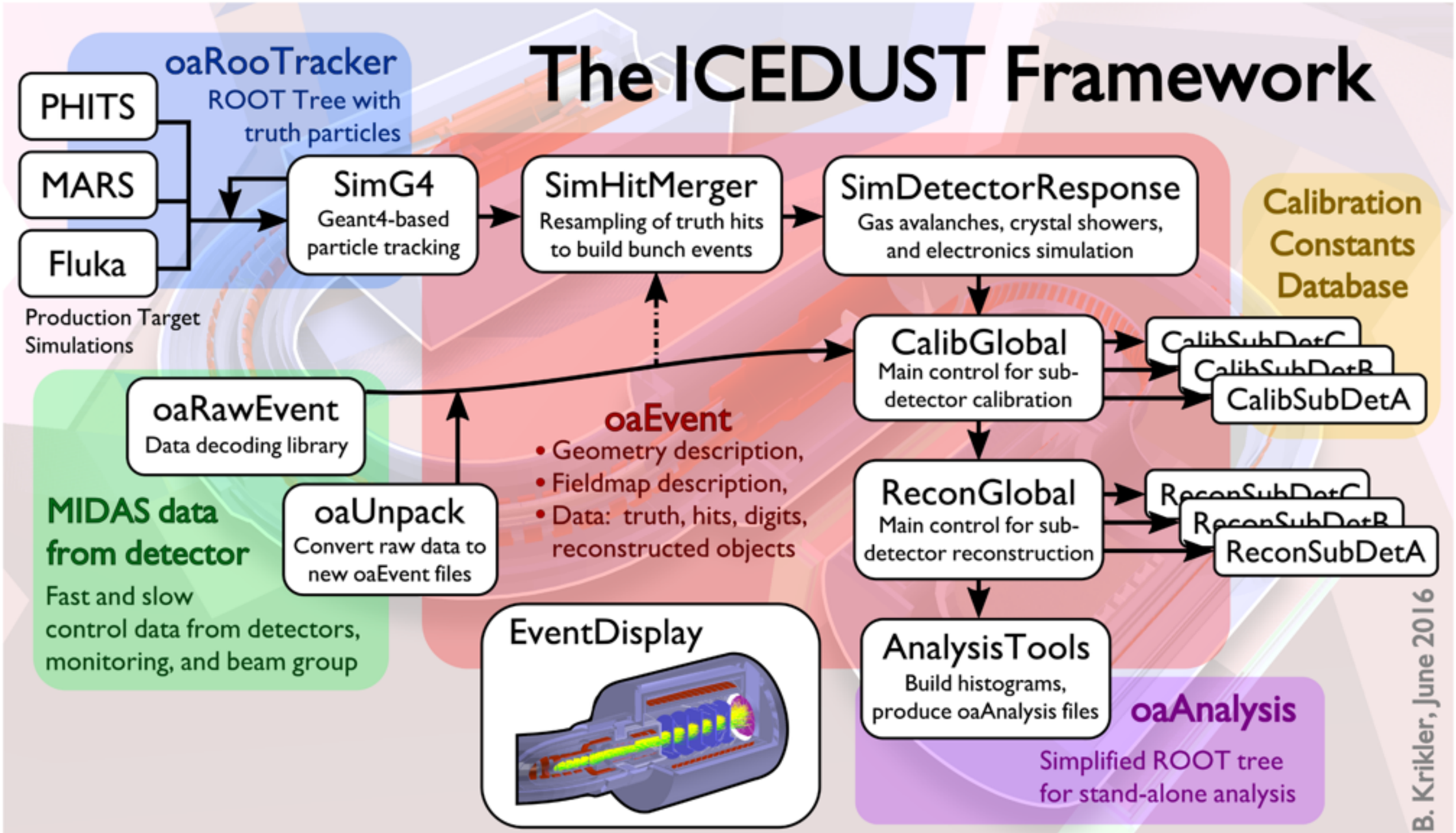


- **ECAL pretrigger** being developed @ BINP
  - Dedicated trigger front-end for ECAL
  - 40MHz, 10bit ADC
  - Cyclone IV (Altera) for processing ADC data
  - Data transfer to FCT through FMC connector
  - Succeed to observe the signal

- **COTTRI** being developed @ KEK
  - General purpose trigger front-end
  - 100MHz 8bit ADC
  - Artix-7 (Xilinx) for processing analog/digital signals
  - Data transfer to DAQ PC and FCT/FC7
  - ~150ns latency measured, demonstration in StrECAL beam test succeeded

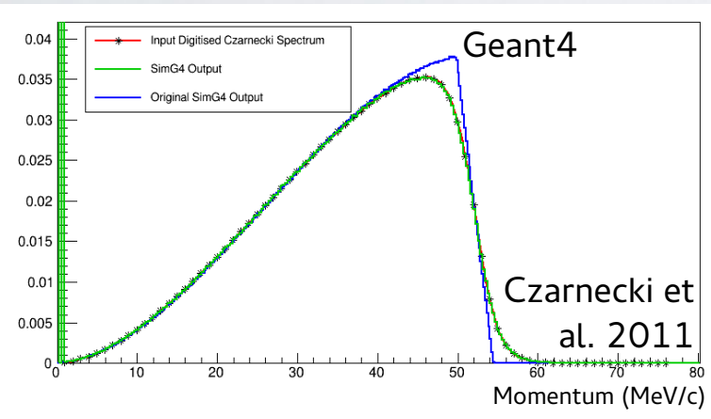
Software

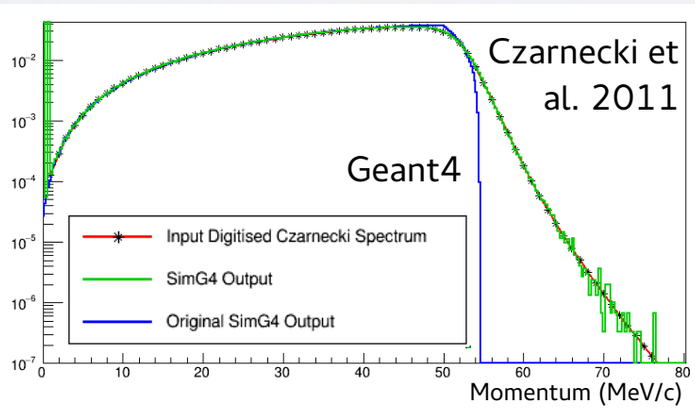
ICEDUST Overview

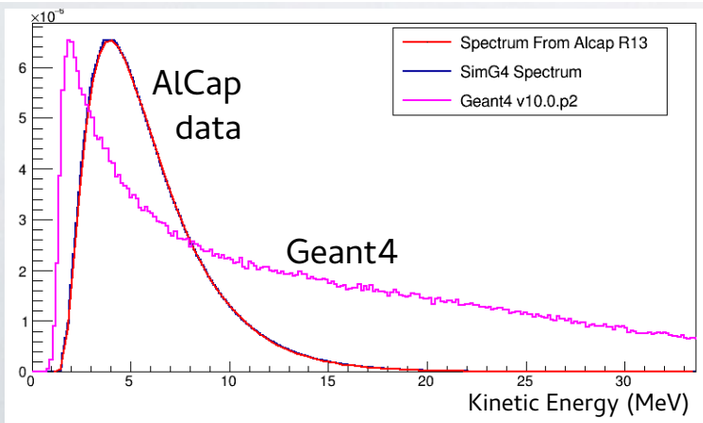


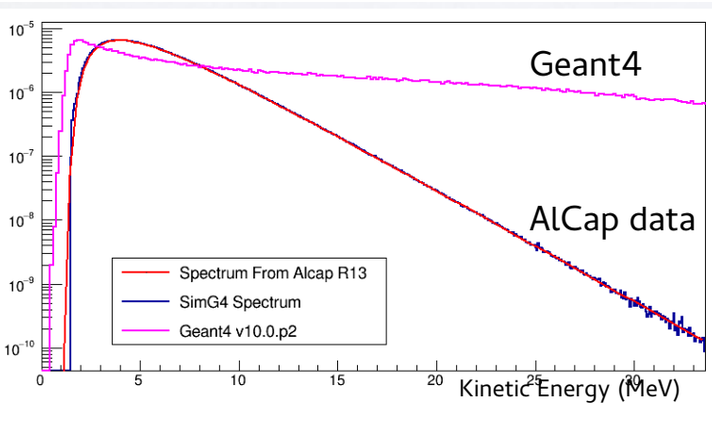
Simulation

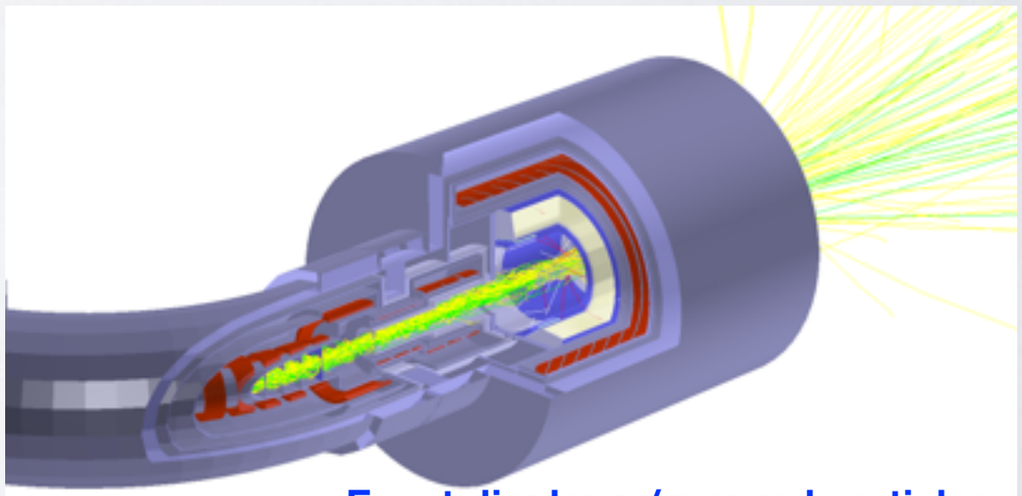
- Based on Geant4
  - DIO and proton emission from muon capture refined based on the paper*/AlCap result
  - Events can be merged to simulate the bunched beam structure
  - Detector response has been implemented as well (version 1)
- Large scale MC samples have been produced for several important study items
  - Trigger study, tracking w/ pileup, beam measurement, etc.
  - ~18,000 bunch trains for CyDet generated on Yandex machine
    - ~100TB data stored on iRODS@CCIN2P3





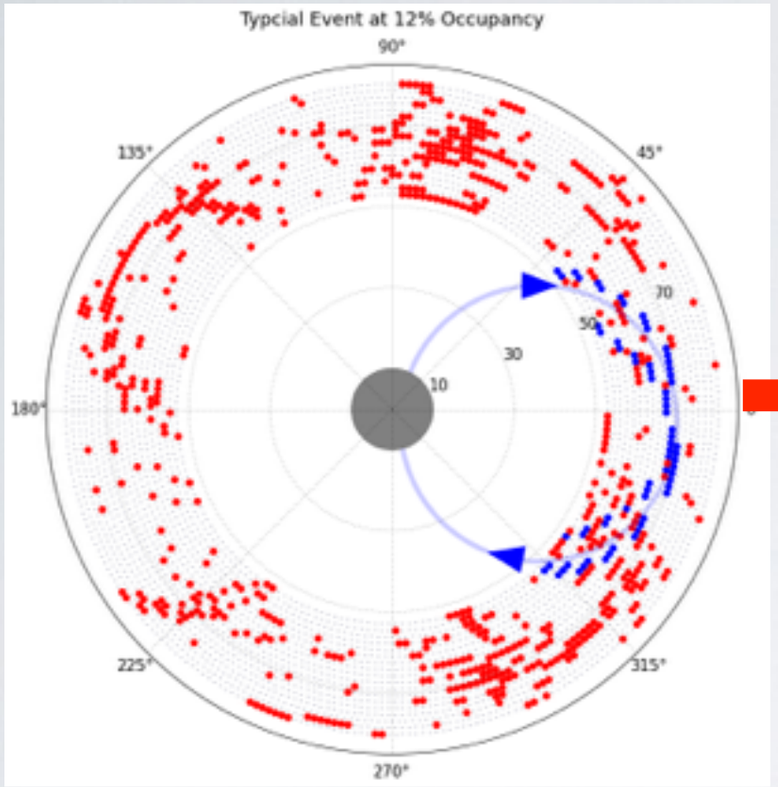




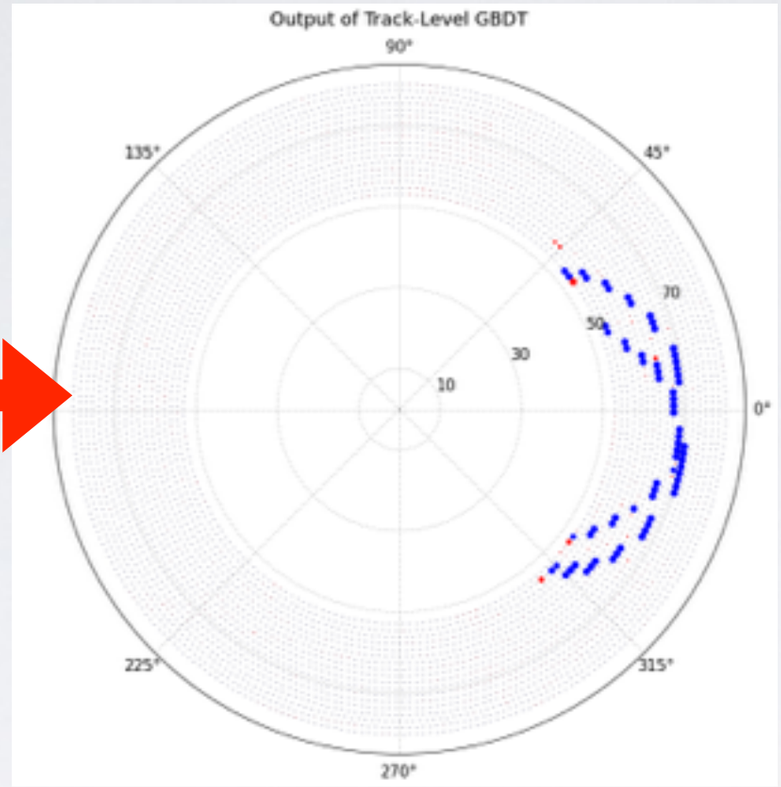


Event display w/ merged particles

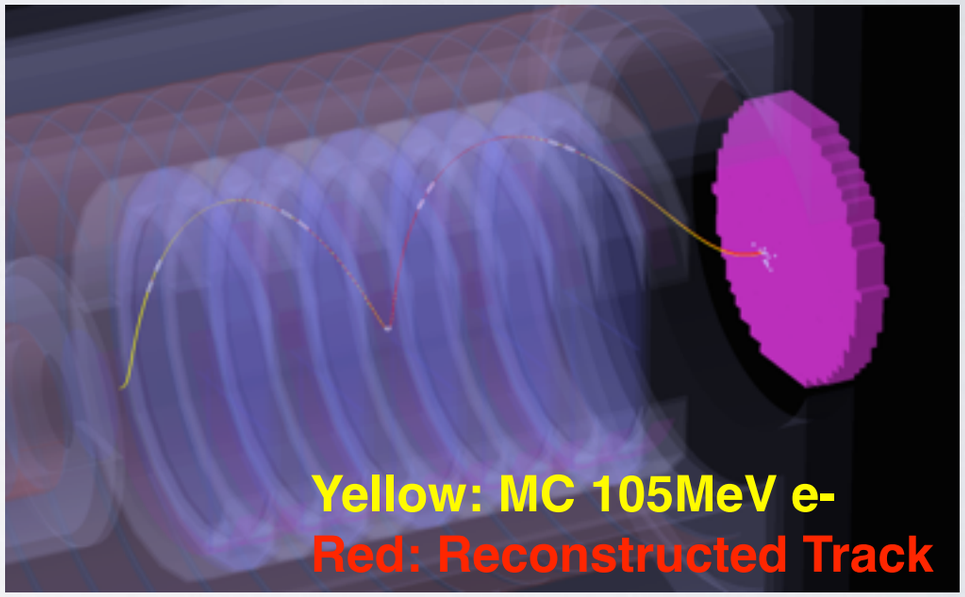
Reconstruction



Signal track with BG
Blue: signal
Red: BG



After apply track finding based on
1. Gradient Boosted Decision Tree
2. Hough based



- Development of reconstruction in ICEDUST is underway
  - All standalone studies to be migrated to ICEDUST soon
- Track Fitting based on GENFIT2 is fully functional in ICEDUST
  - Provide the same track fitting algorithm both for StrawECAL & CyDet
- Further detector optimizations are available with ICEDUST now

Phase-I Sensitivity and Backgrounds

Single Event Sensitivity

Event selection	Value	
Online event selection efficiency	0.9	
DAQ efficiency	0.9	
Track finding efficiency	0.99	
Geometrical acceptance + Track quality cuts	0.18	
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93	$103.6 < p_e < 106.0$ MeV/c
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3	$700 < t_e < 1170$ ns
Total	0.041	

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

Number of muons stopped inside targets

Fraction of muons to be captured by Al target = 0.61

Fraction of μ-e conversion to the ground state = 0.9

- 3×10^{-15} S.E.S. achievable in ~150 days of DAQ time corresponds to $N_\mu=1.5\times10^{16}$

Backgrounds

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.

Due to incident protons arriving between the main proton bunches

Due to particles delayed inside capture/transport solenoids

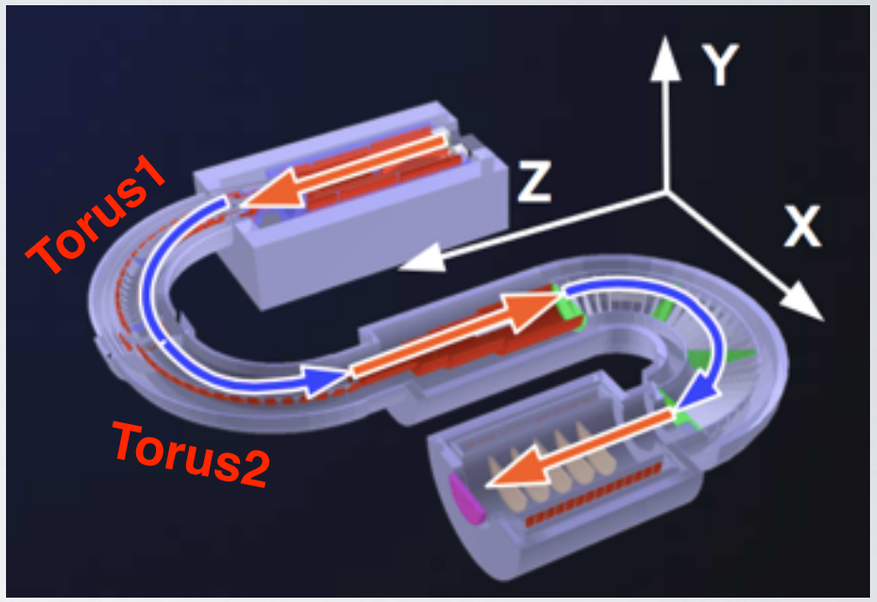
- Normalized to a 3×10^{-15} of S.E.S., assuming extinction factor=3×10^{-11}
- To be measured directly in Phase-I beam measurement

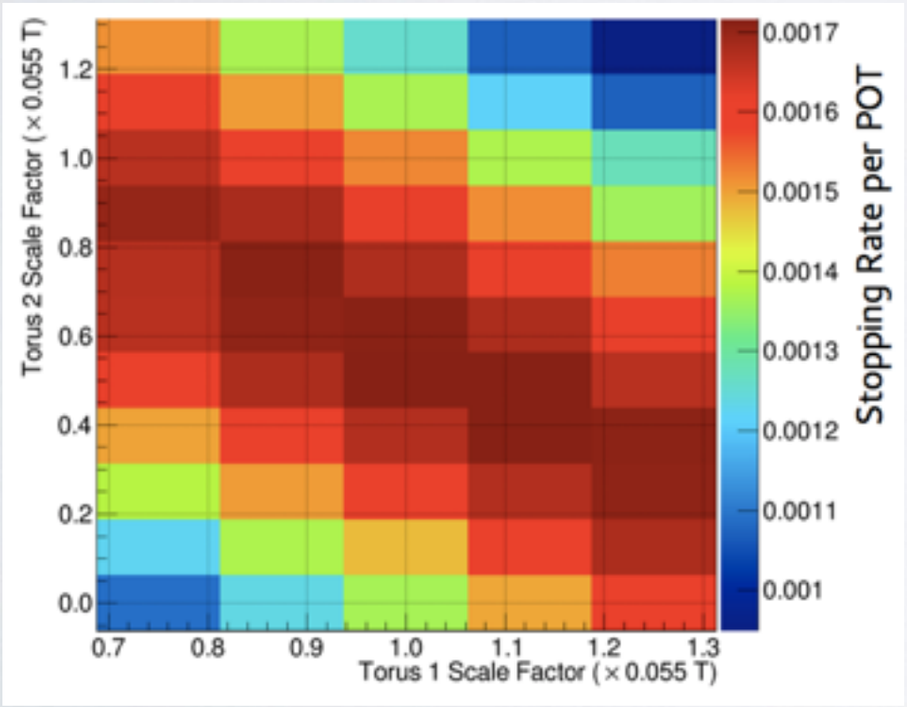
Phase-II Study

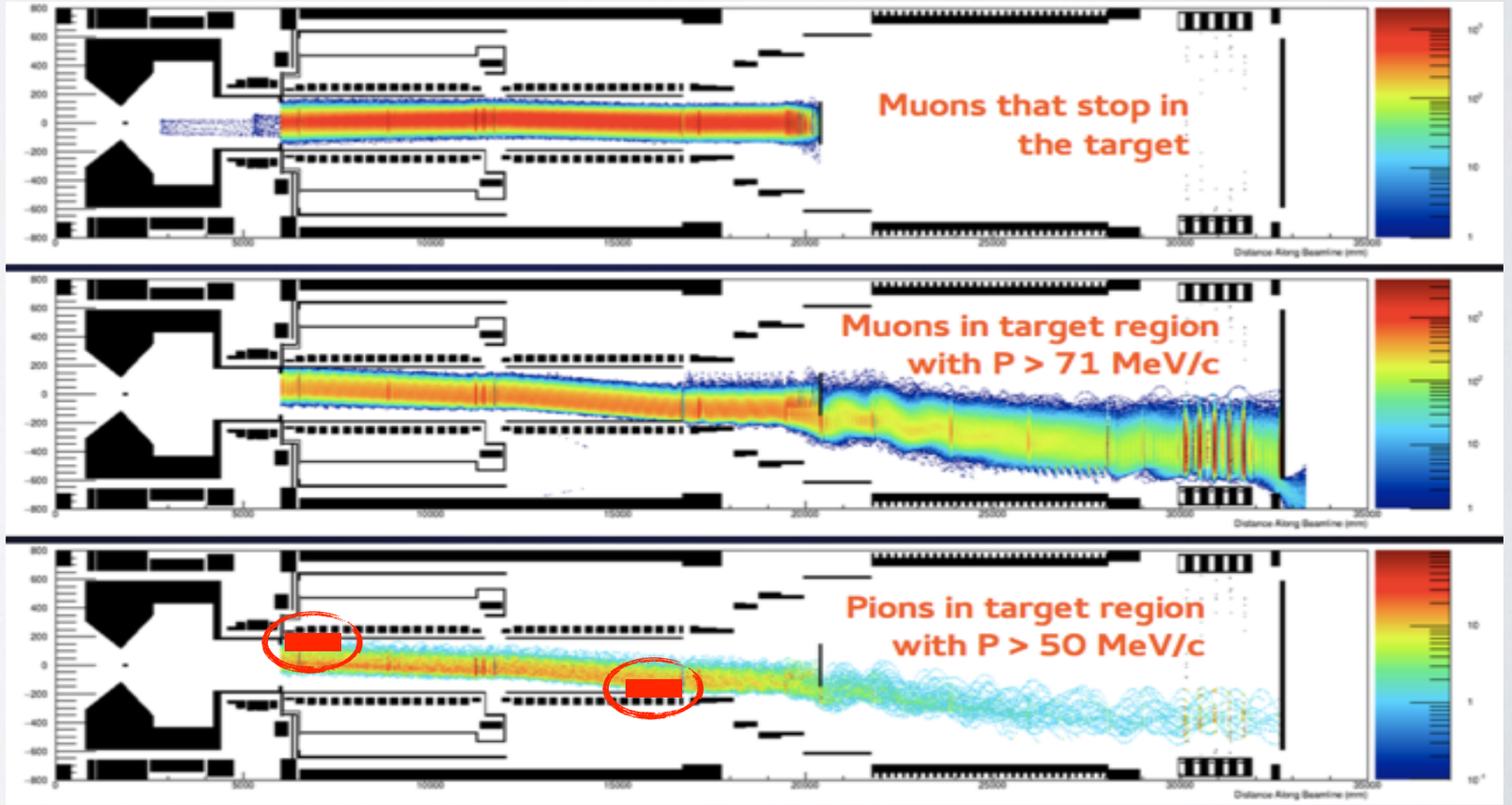
Phase-II Study

Forthcoming PhD Thesis
(Ben Krikler)

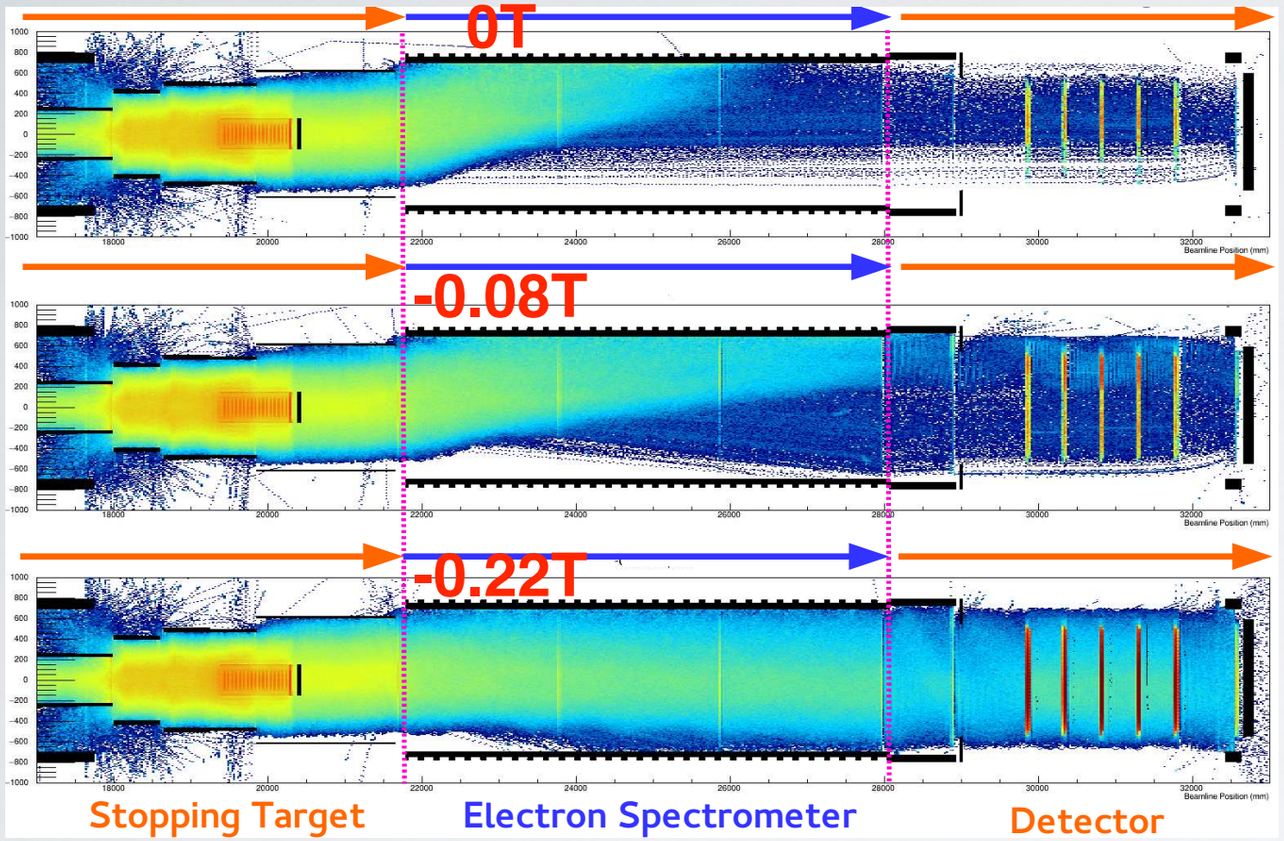
- Dipole field optimizations for muon transport solenoid and Electron spectrometer
  - Maximize the number of muon stopped in the target
  - Maximize signal acceptance
- Collimator optimization
  - Minimize the backgrounds while keeping the muon yield high enough
  - Careful study is needed

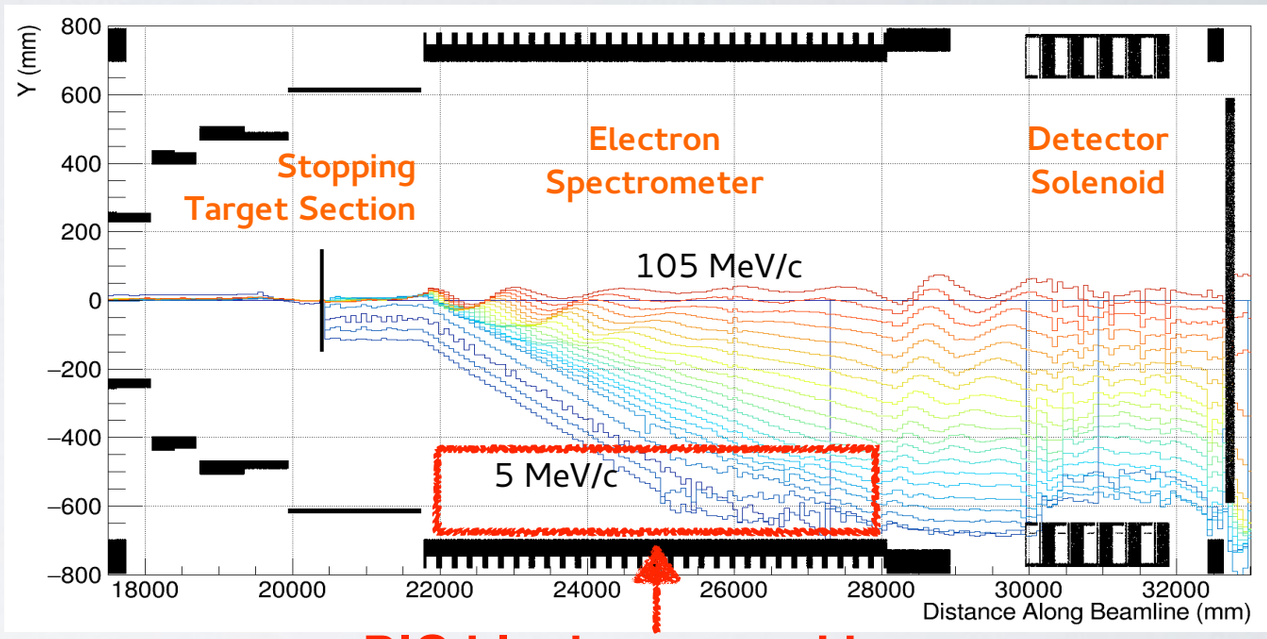






Electron Spectrometer

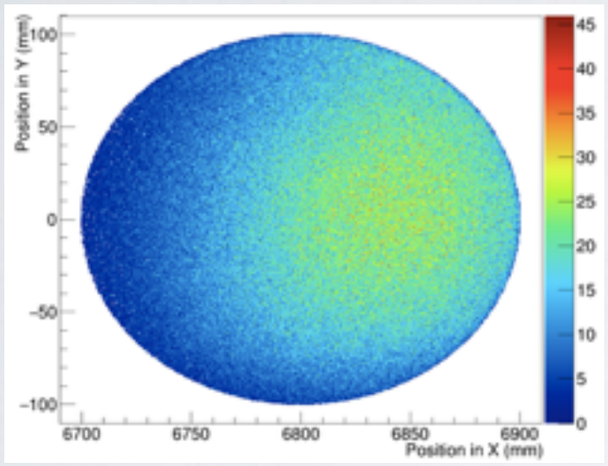


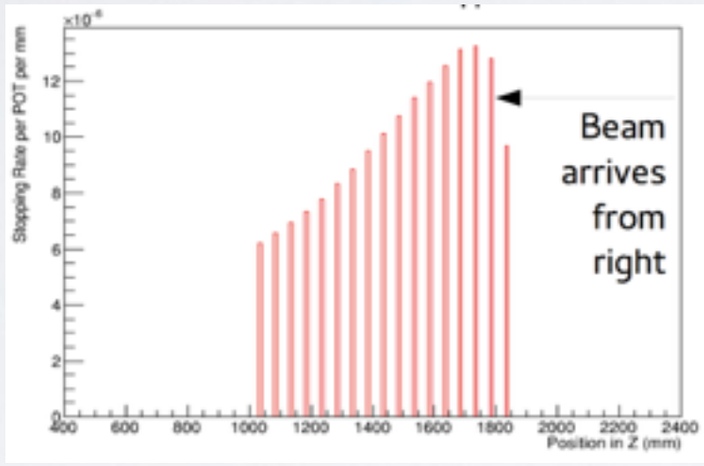


- Adjustable dipole field allow us to:
  - Optimize the acceptance for 105MeV/c electrons
  - Reduce the hit rate from lower momentum electrons if it's high

Phase-II S.E.S.

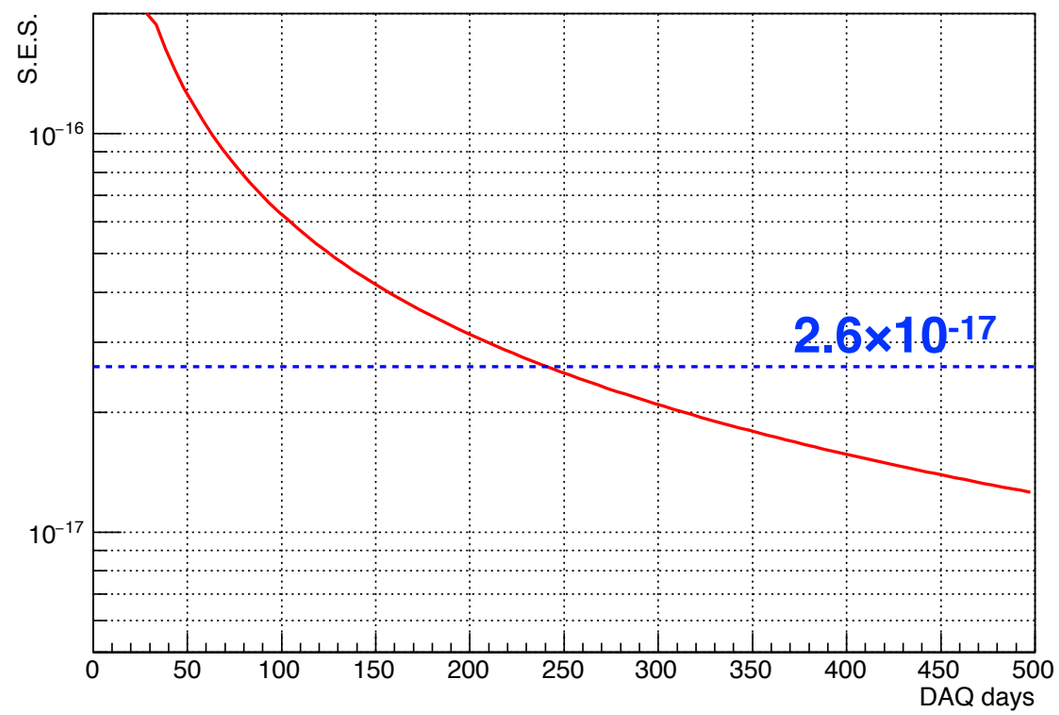
- To be conservative, collimators in the muon transport solenoid are not included yet
- Muon stopping rate = **1.7×10^{-3}** / POT (5×10^{-4} in Phase-I)
- Backgrounds estimation is ongoing
- S.E.S. of **2.6×10^{-17}** with ~240 days DAQ



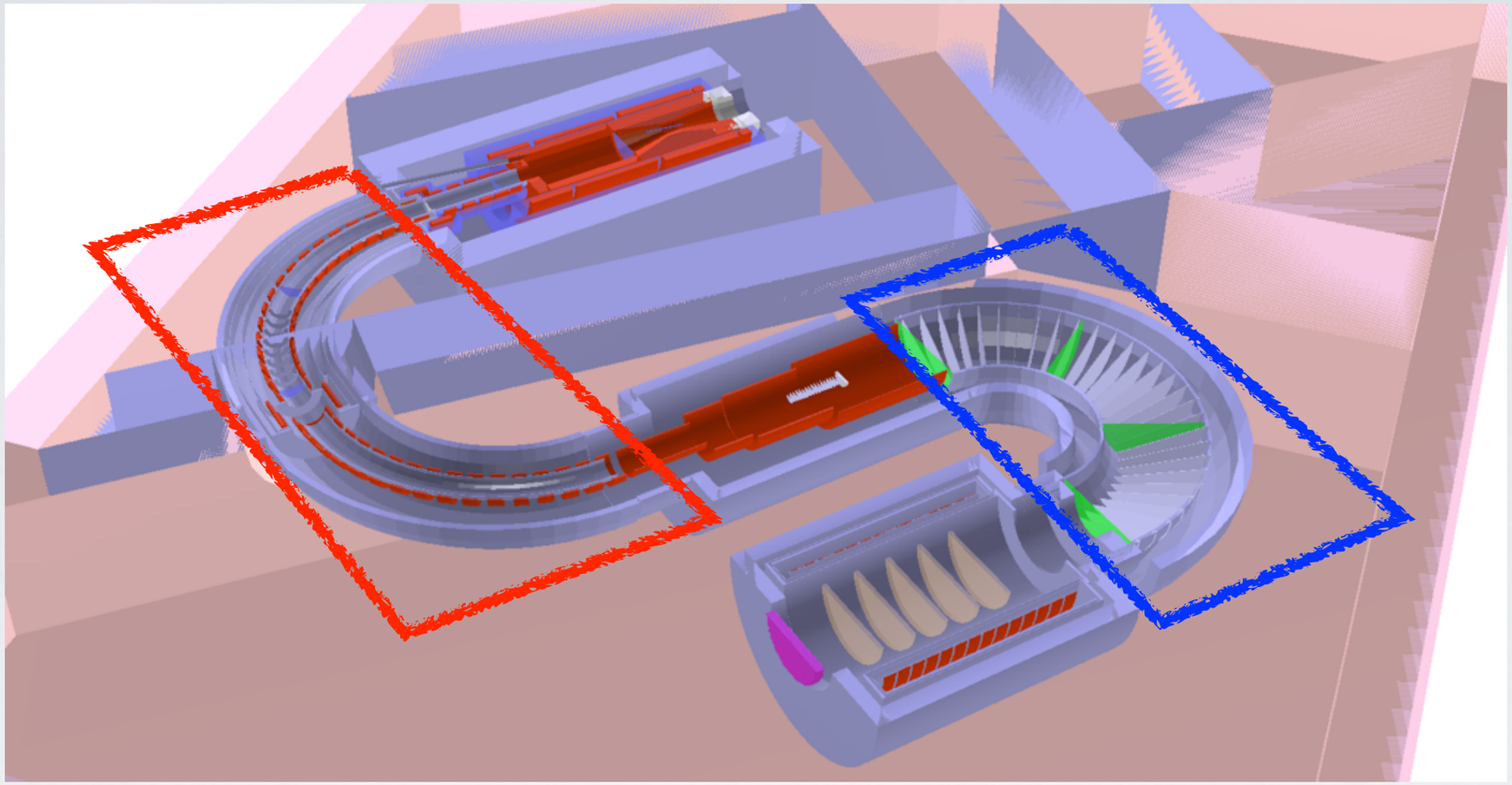


	Acceptance
Geometric	0.22
Momentum Cut	0.80
Timing	0.53
Total Truth-level Signal Acceptance:	**0.093**
with CDR TDAQ + Recon. efficiency	0.046

S.E.S. Curve as a function of accumulated DAQ time



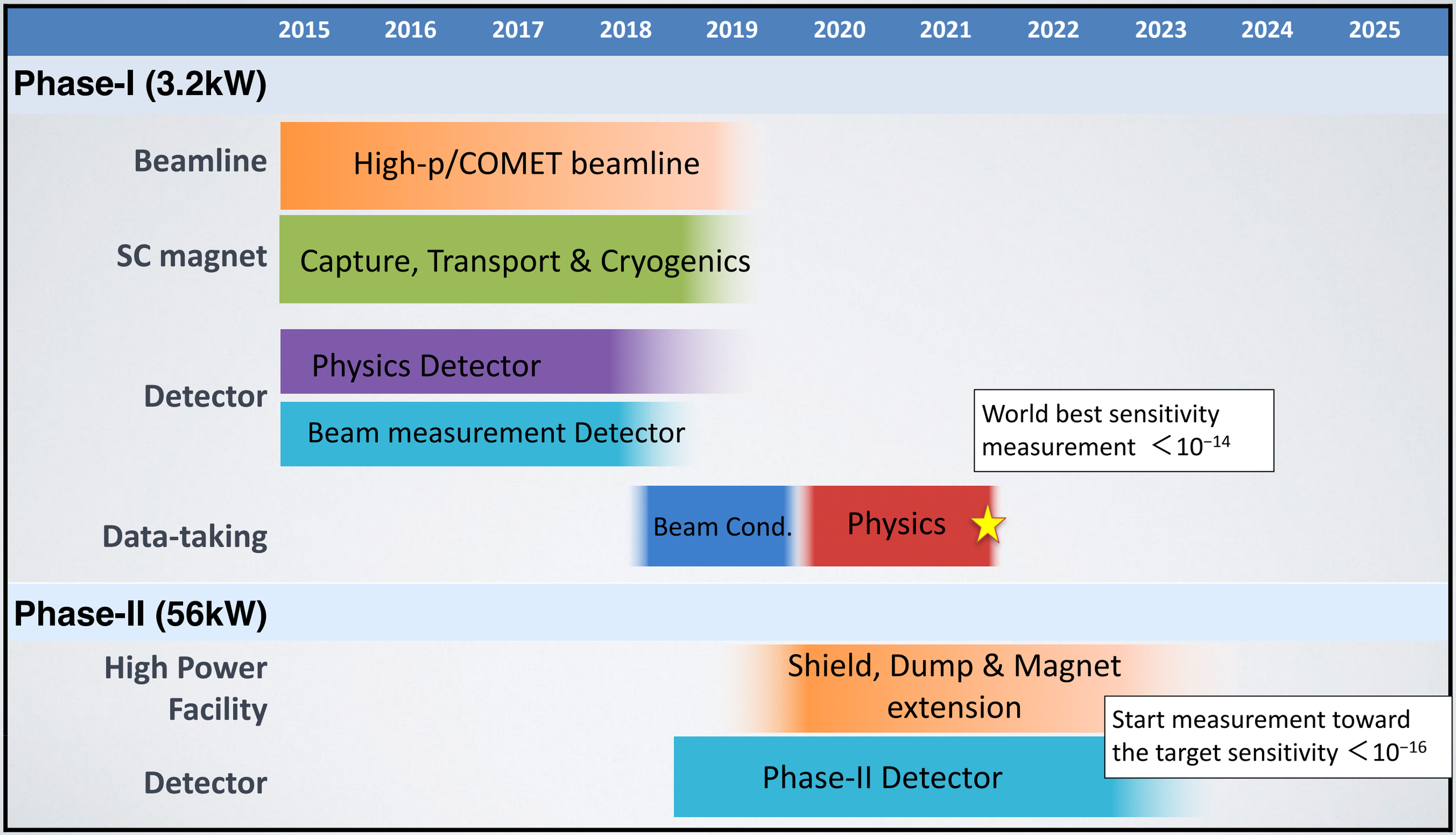
Summary of COMET Phase-II



- **COMET Phase-II**
  - C-shaped transport solenoid with a tunable dipole field
    - Can optimize later
  - C-shaped electron spectrometer
    - Can select electron momentum and suppress hit-rate in detectors
  - Cannot share the beam with other hadron experiments compared to Mu2e

Summary

Schedule


2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Phase-I (3.2kW)
Beamline
High-p/COMET beamline
SC magnet
Capture, Transport & Cryogenics
Detector
Physics Detector
Beam measurement Detector
World best sensitivity measurement ＜10−14
Data-taking
Beam Cond.
Physics
Phase-II (56kW)
High Power Facility
Shield, Dump & Magnet extension
Start measurement toward the target sensitivity ＜10−16
Detector
Phase-II Detector

Summary

- COMET searches for μ-e conversion with S.E.S of 3×10^{-15} (2.6×10^{-17}) in Phase-I (Phase-II) @J-PARC
  - Phase-II S.E.S. with 1 year DAQ is comparable to that of Mu2e
- A lot of studies are intensively ongoing
- Recent Highlights
  - Completion of CDC construction
  - StrawECAL combined test
  - Daisy chain for EROS/ROESTI
  - Beam test for Diamond detector
  - Large scale MC production
  - Revisited Phase-II study with updated magnetic fields / geometry / software
- Data taking will start in 2018/2019 for Phase-I
- Phase-II can be a few years after Phase-I depending on the budget
  - Almost all R&Ds for Phase-II will be completed in Phase-I

Backup