THE COMET EXPERIMENT

to Search for μ-e Conversion at J-PARC

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On behalf of the COMET collaboration

WIN2017, UC Irvine, Irvine, CA, USA

The 26th International Workshop on Weak Interaction and Neutrinos

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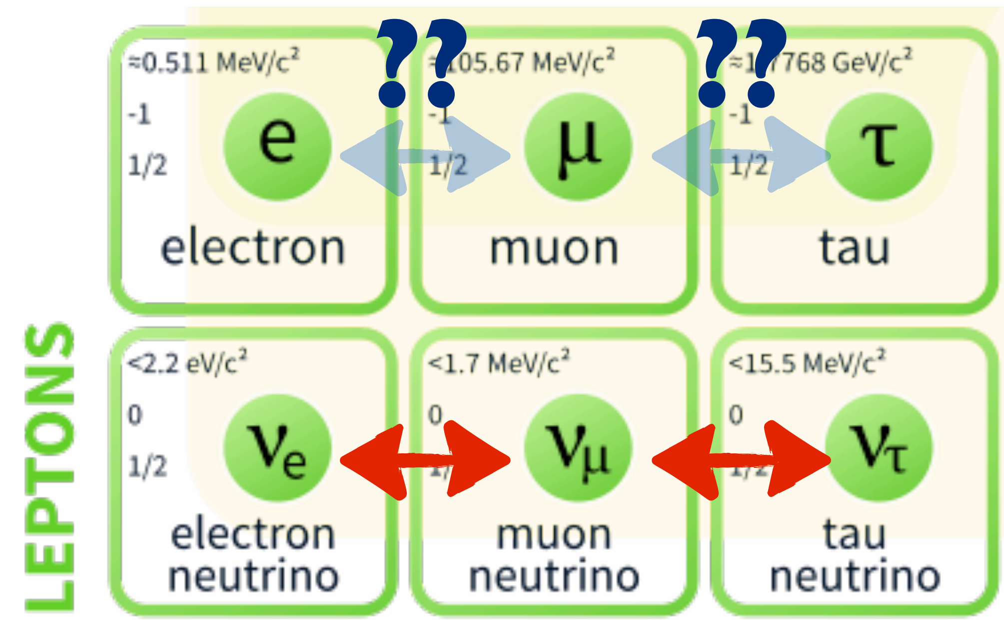
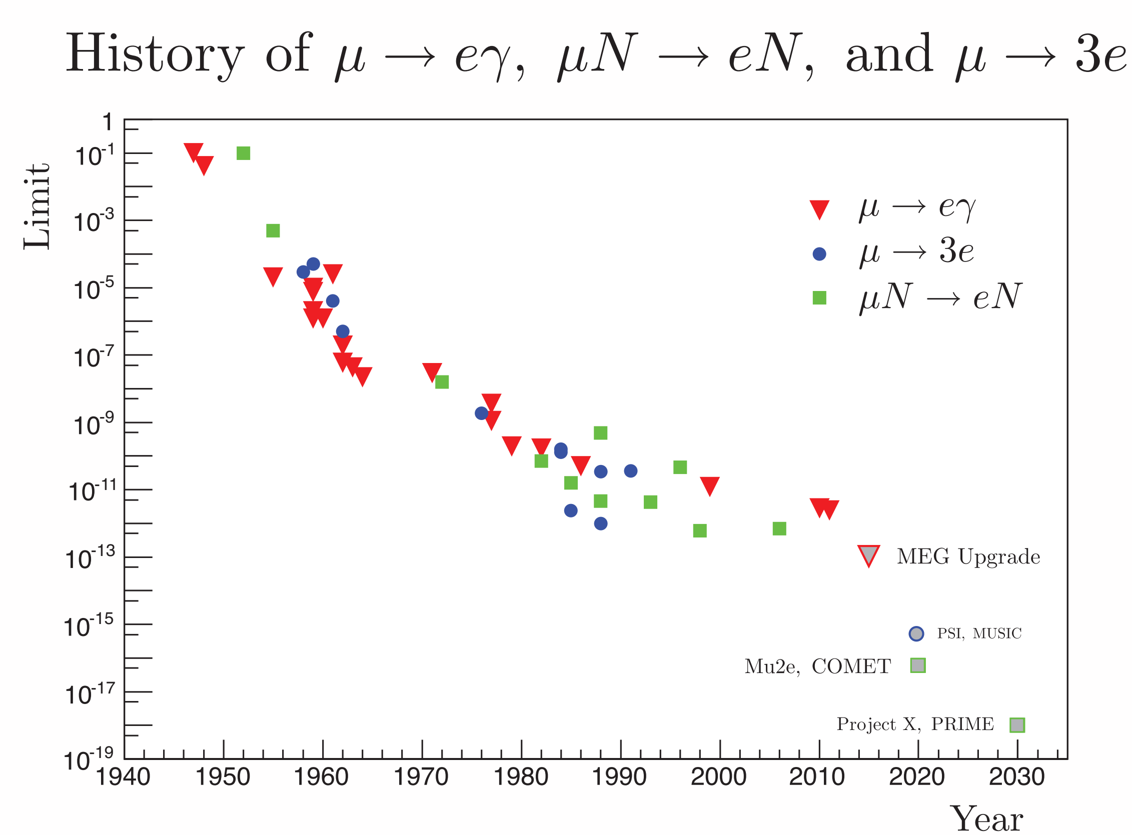
PHYSICS -LEPTON FLAVOR VIOLATION-

Lepton Flavor Violation

- ✦ Neutral lepton flavor violation process
  - ★ Neutrino oscillation.
  - ★ The standard model (SM) was extended.
- ✦ **Charged lepton flavor violation**
  - ★ Many experiments but no discovery
    - ❖ μ → eγ
    - ❖ μ → 3e
    - ❖ **μN → eN**
    - ❖ and many...
  - ★ A clear signal of new physics

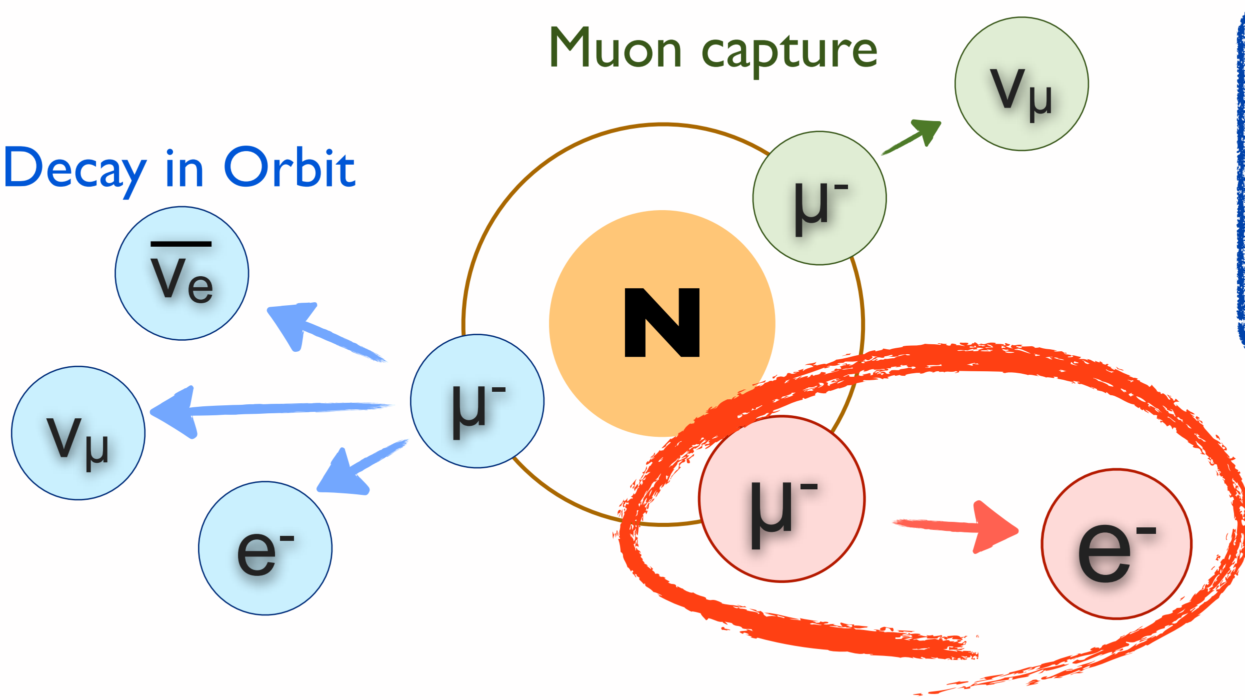


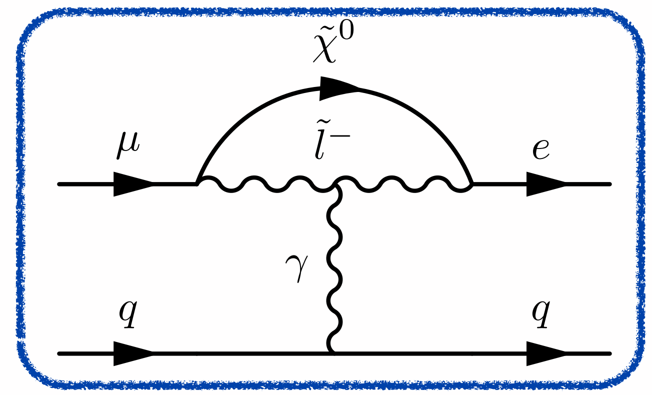
From wikipedia



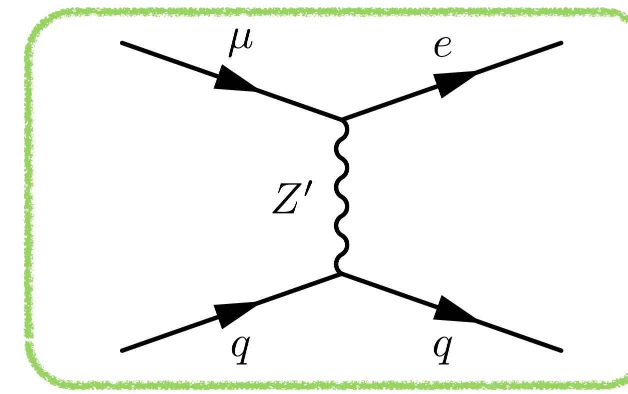
From Physics Reports 532: 27-64, Nov 2013

Muon-to-Electron Conversion





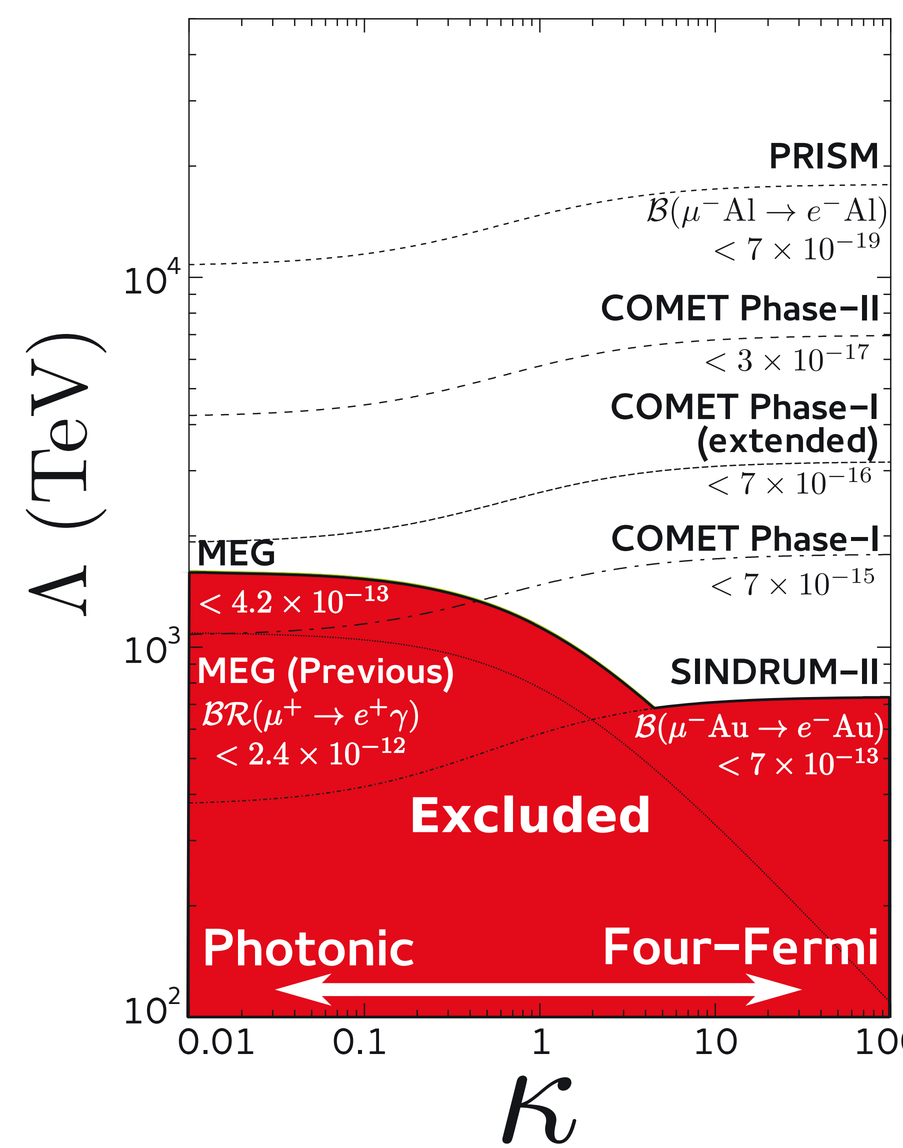
Photonic process



Four-fermion process

Muon-to-electron (μe) conversion

- A charged lepton flavor violation process
  - Muon decays to single electron w/o neutrinos.
  - Strongly suppressed in the SM including the neutrino oscillation
  - Branching ratio: BR(μN→eN) < 10^{-54}
- Reach **~10^{-15}** at in many Beyond SMs.
  - SUSY-GUT, Z'
- Model discrimination with μ→eγ

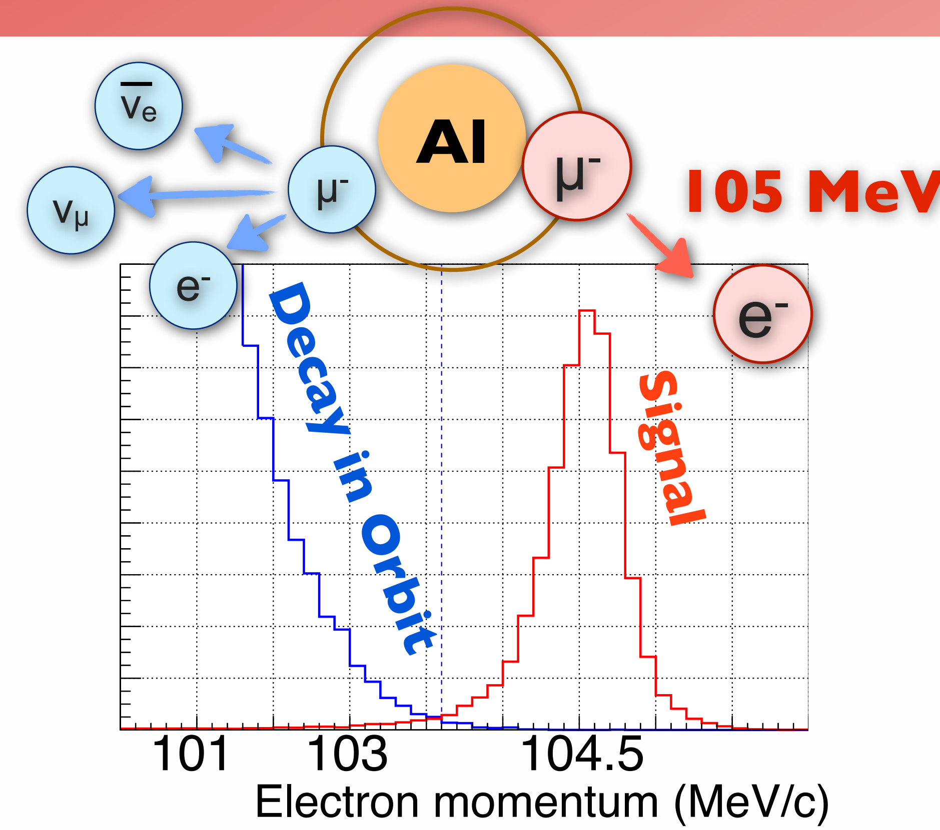


From PhD thesis by Ben Krikler

Experimental Principle

Signal & intrinsic BGs

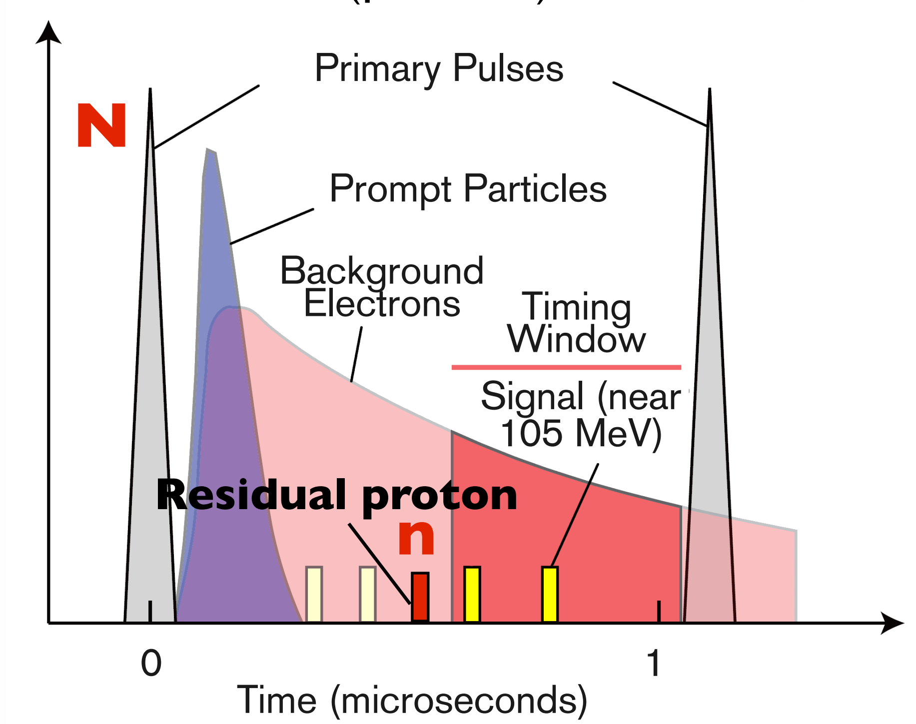
- Signal: $\mu^- + N \rightarrow e^- + N$
  - Monochromatic energy of **105 MeV** (Al)
- Dominant intrinsic backgrounds: **decay-in-orbit (DIO)**
  - Contaminate the signal region w/ a finite detector resolution.
  - **Momentum resolution < 200 keV/c** is required.



Electron momentum spectrum
w/ BR(μN→eN) = 10^{-15}

High intense muon beam and beam BGs

- World-class intensity proton beam @ J-PARC.
  - Gain high statistics of muons.
  - **An effective transport line from π to μ required.**
  - Backgrounds arise from the proton and its secondaries.
    - Antiproton, radiative pion capture, muon decay in flight, etc...
- Bunched beam structure
  - **Delayed timing window** for masking the beam BGs.
  - The fraction of residual protons between the bunches (**extinction** = n/N in the right fig.) < 10^{-9}



Bunched Beam Structure & Delayed Timing Window

COMET Collaboration

International Collaboration

- ✦ 15 countries
- ✦ 33 institutes
- ✦ **>175 collaborators**

COMET Experiment

Searching for μ-e conversion at J-PARC

- The final goal: **O(10^{-17})** sensitivity.
  - 10, 000 times improved from the current limit.
- Building the facility and muon transport line.
- Two staging plan
  - Phase-I and Phase-II

Phase-I

- ✓ **Sensitivity O(10^{-15})**
- ✓ **Physic measurement**
  by a cylindrical tracker (CyDet)
- ✓ **Beam & BG measurement**
  by a tracker & ECAL (StrECAL)

Phase-II

- ✓ **Sensitivity O(10^{-17})**
- ✓ **Physic measurement**
  by StrECAL

Again used

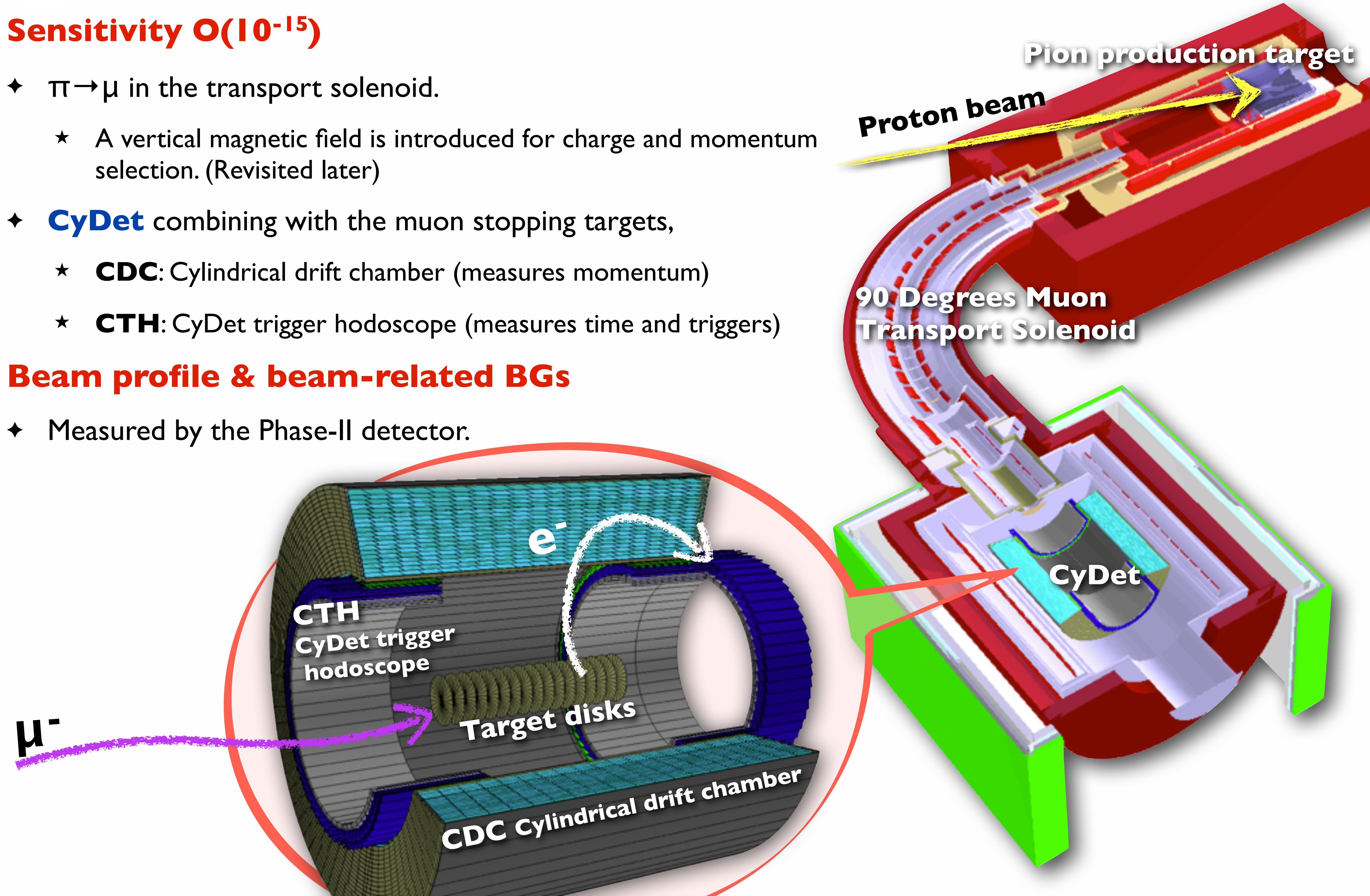
Phase-I

Sensitivity O(10^{-15})

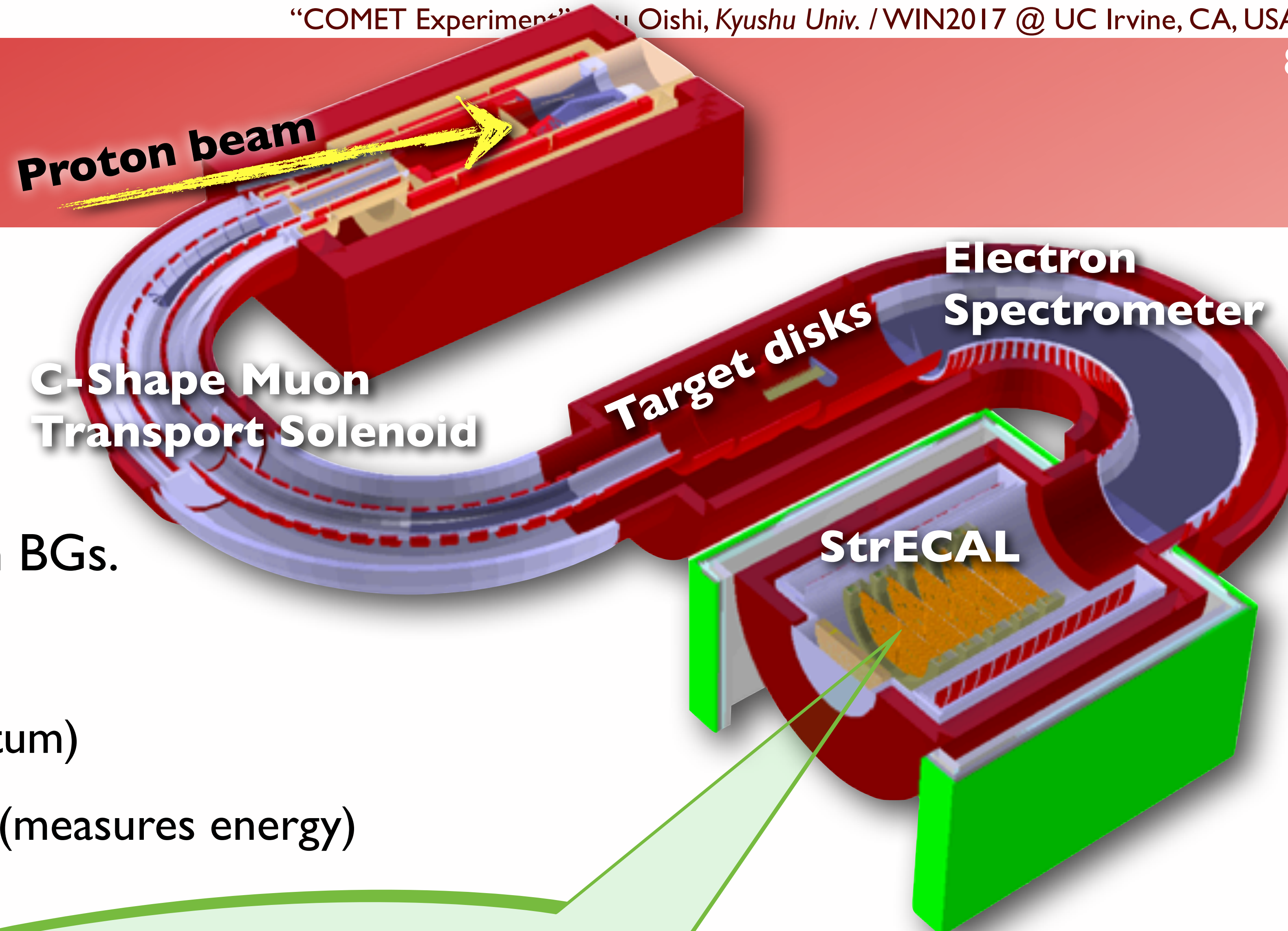
- π→μ in the transport solenoid.
  - A vertical magnetic field is introduced for charge and momentum selection. (Revisited later)
- **CyDet** combining with the muon stopping targets,
  - **CDC**: Cylindrical drift chamber (measures momentum)
  - **CTH**: CyDet trigger hodoscope (measures time and triggers)

Beam profile & beam-related BGs

- Measured by the Phase-II detector.

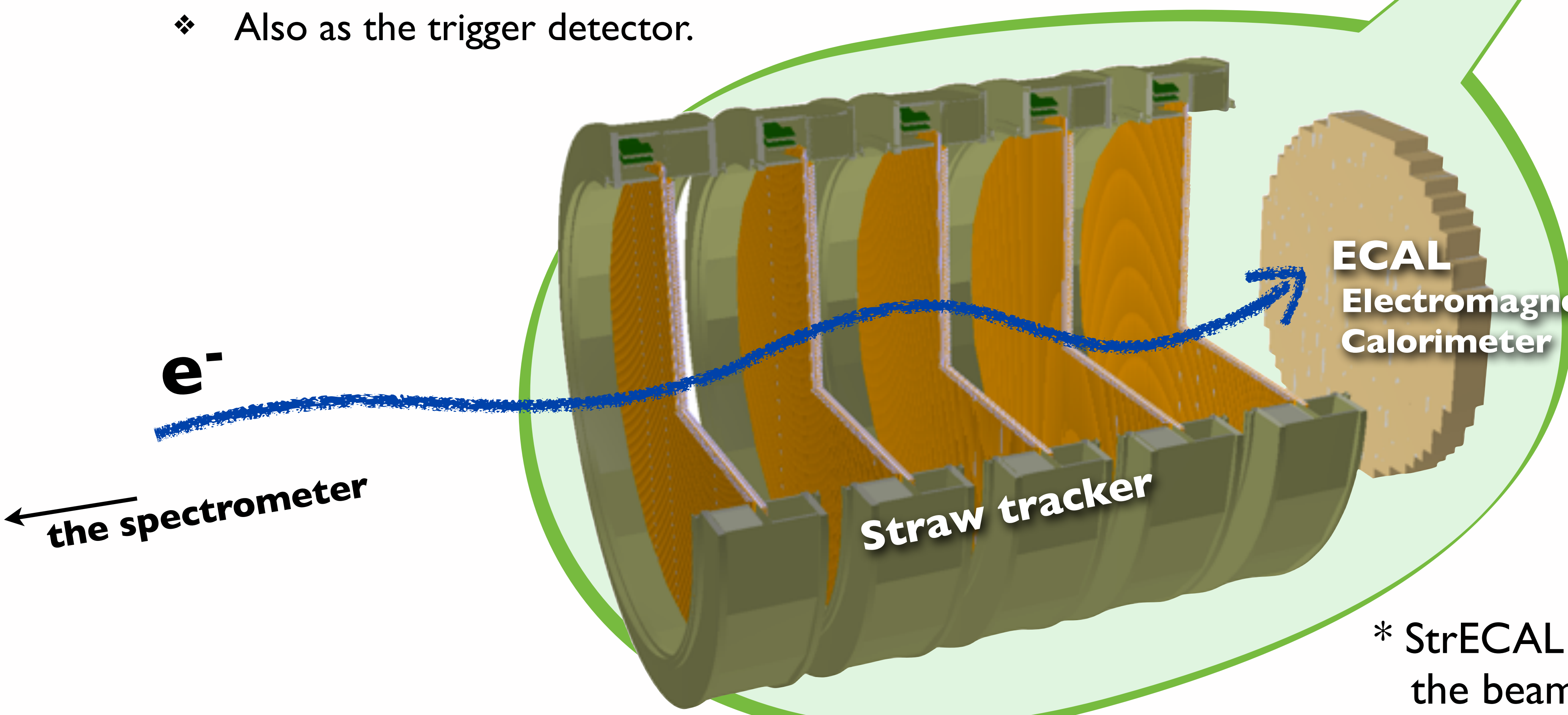


PHASE-II



Sensitivity O(10^{-17})

- Additional transport solenoid.
- Electron spectrometer suppresses low momentum electrons and beam BGs.
- **StrECAL** combining
  - **Straw tracker** (measures momentum)
  - **ECAL**: Electromagnetic calorimeter (measures energy)
    - Also as the trigger detector.



* StrECAL works in Phase-I for the beam & BG measurement, too.

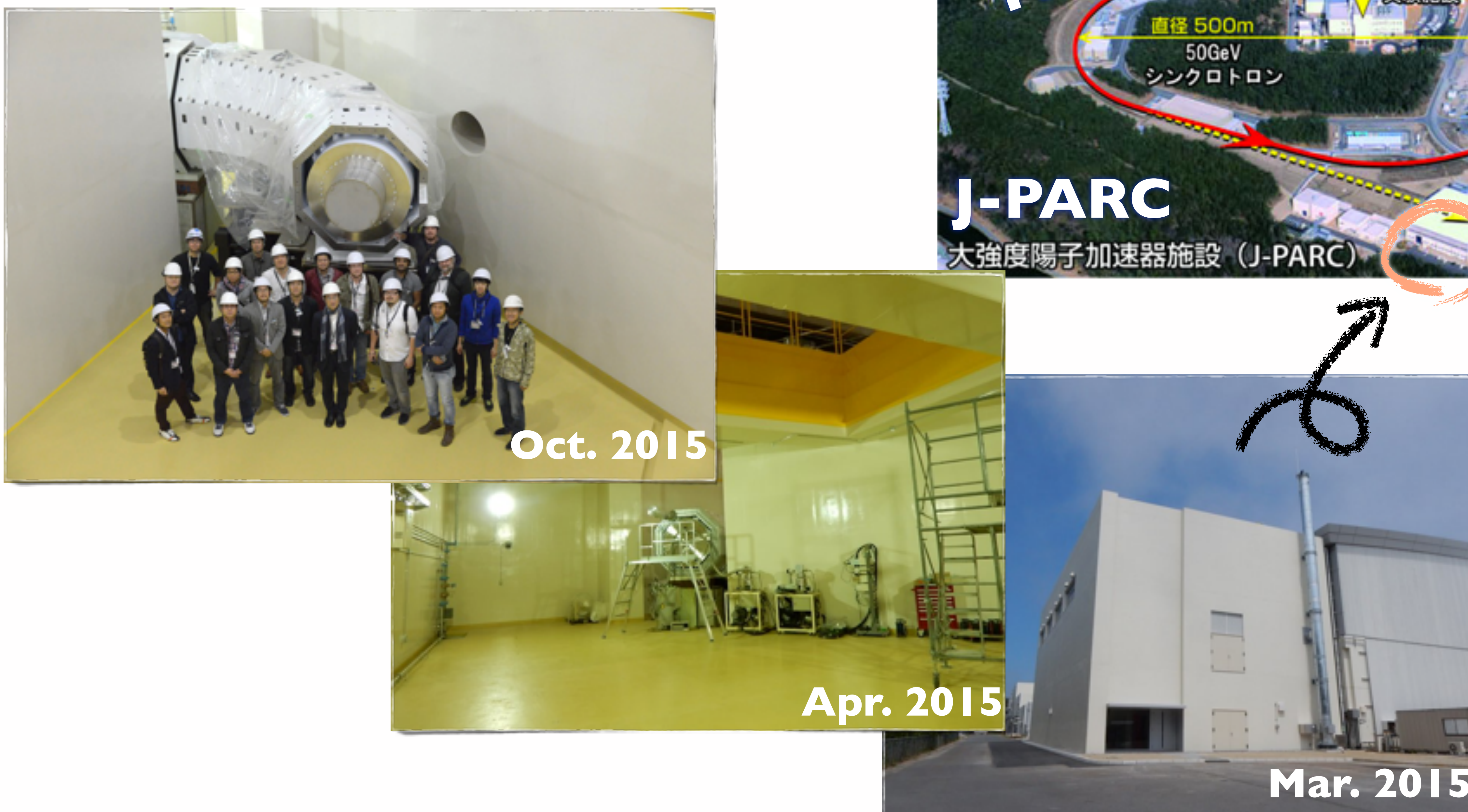
COMET

THE FACILITY

Experimental Facility

COMET Hall

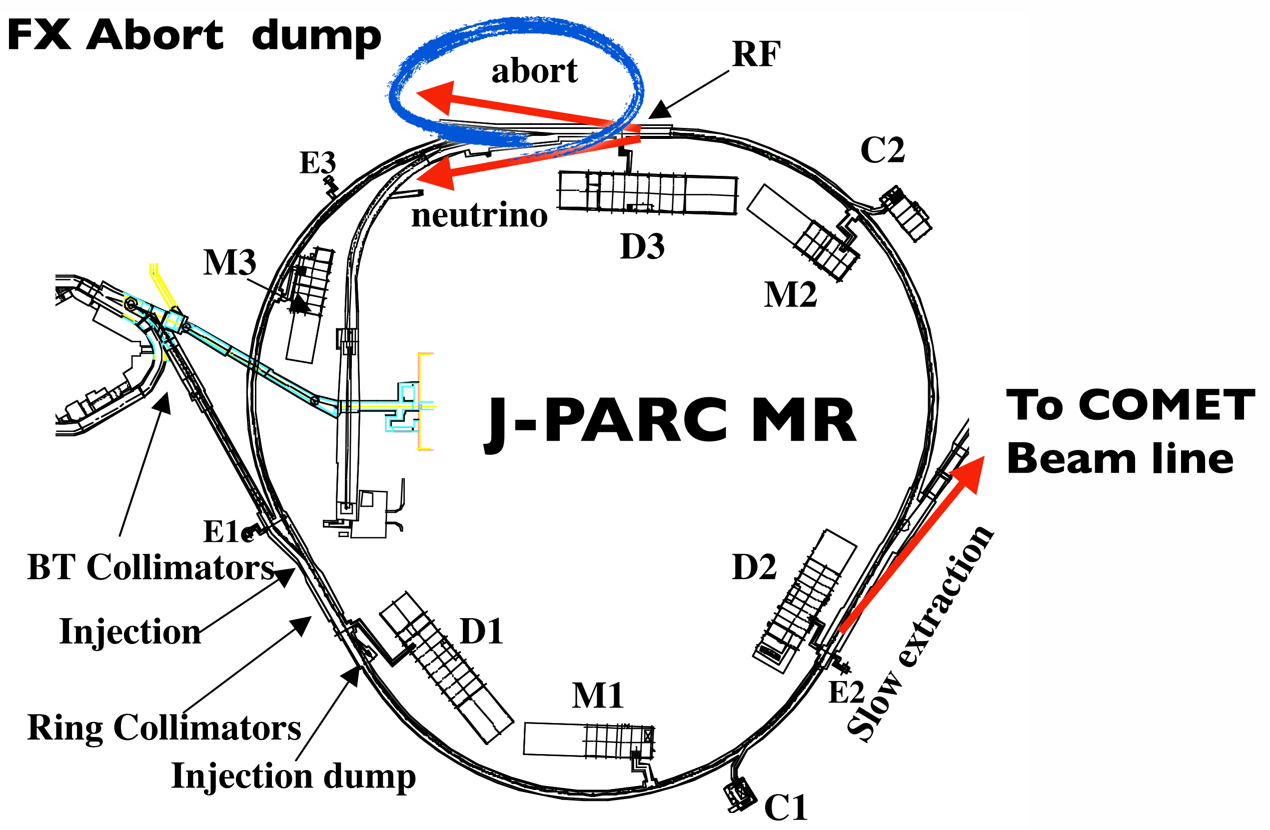
- ✦ Completed in 2015
- ✦ The 90° transport solenoid was installed.

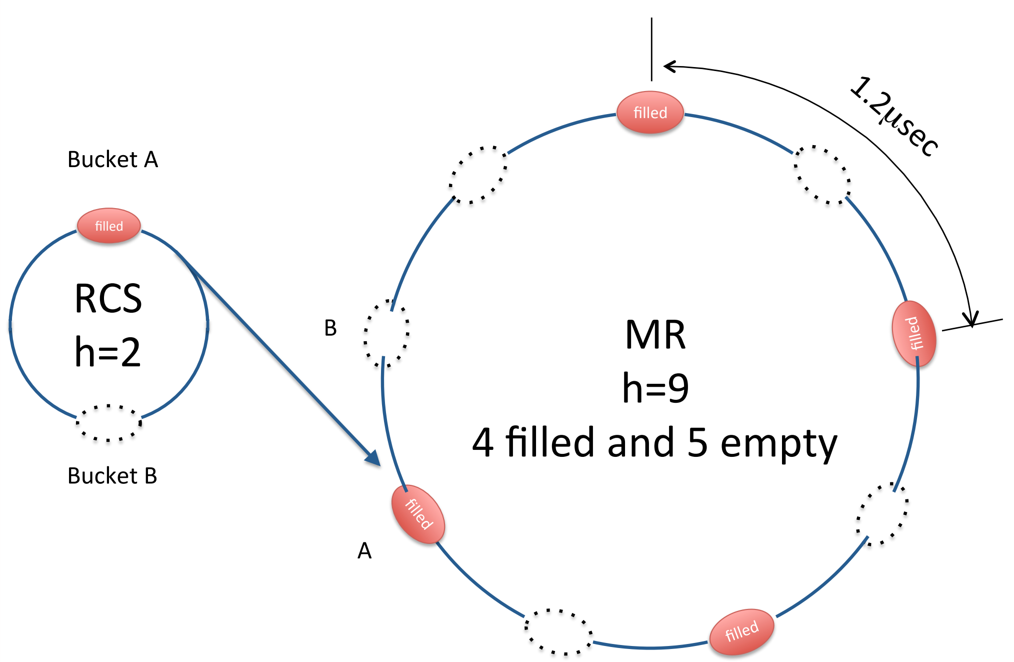


Proton Beam

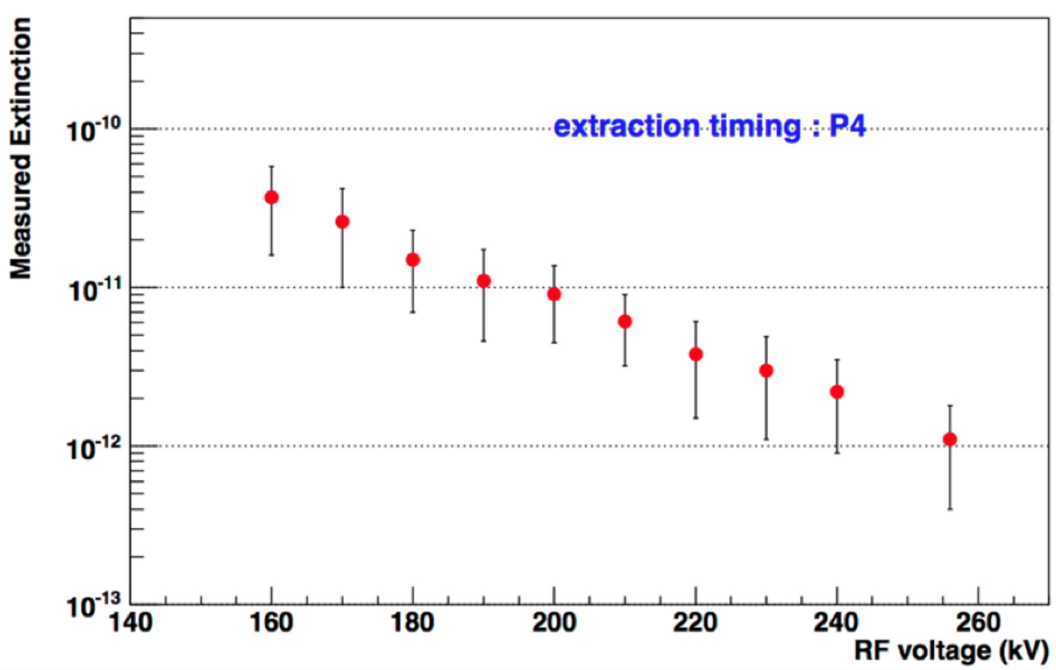
J-PARC Proton Beam for COMET

- 3.2 (56) kW for Phase-I (Phase-II)
- Bunched slow extraction (SX) for the measurement with delayed timing window
- Accelerated up to 8 GeV
  - (1) To minimize antiproton production
  - (2) '**Extinction**' < 10^{-9}
- **The extinction < 3×10^{-11}**
  - @The main ring FX abort dump.





Bunched beam operation for COMET

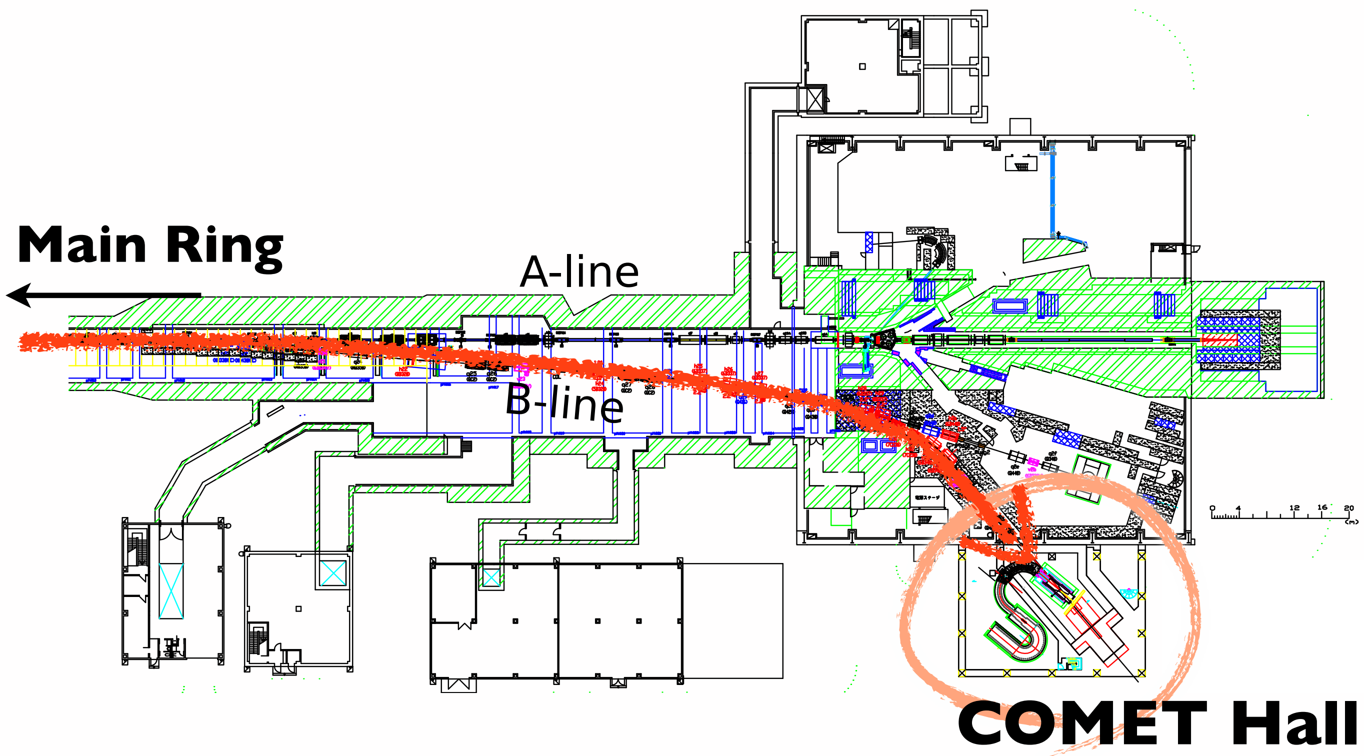


Extinction as a function of the RF Voltage

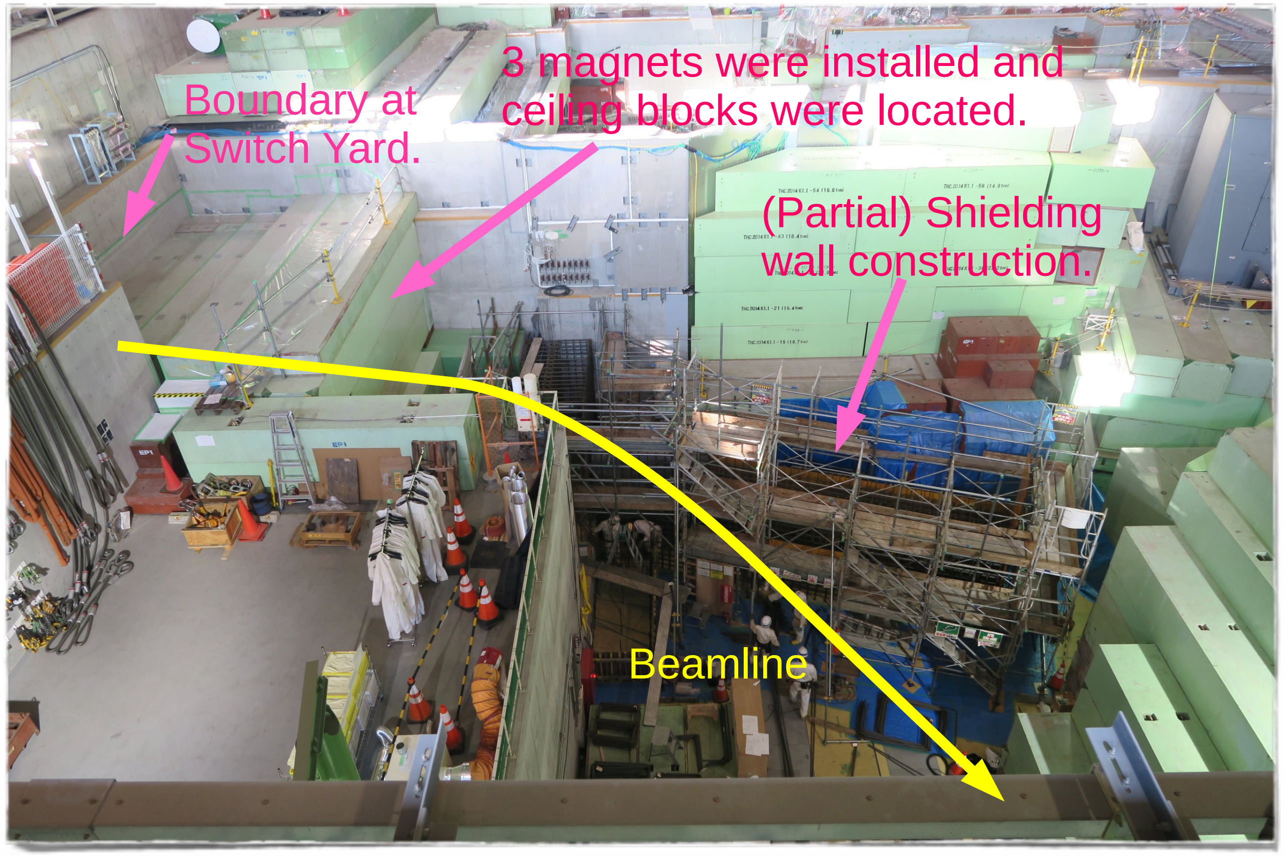
COMET Beam Line

COMET Beam Line

- The beam line design optimization and construction is ongoing.
- **8 GeV SX commissioning will be performed in this year.**



Beam line for COMET (red line)



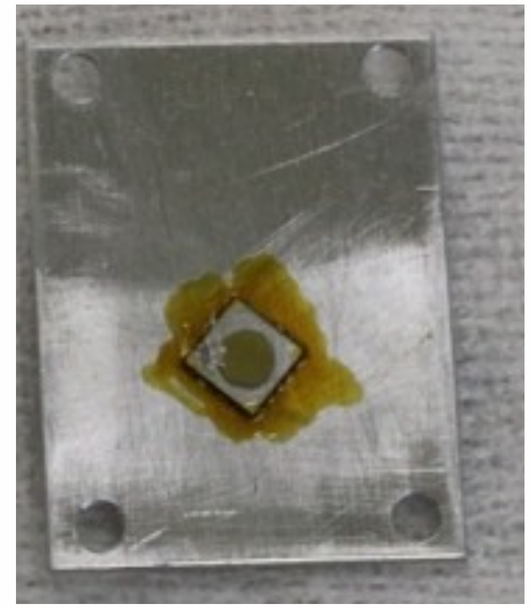
The beam line being constructed

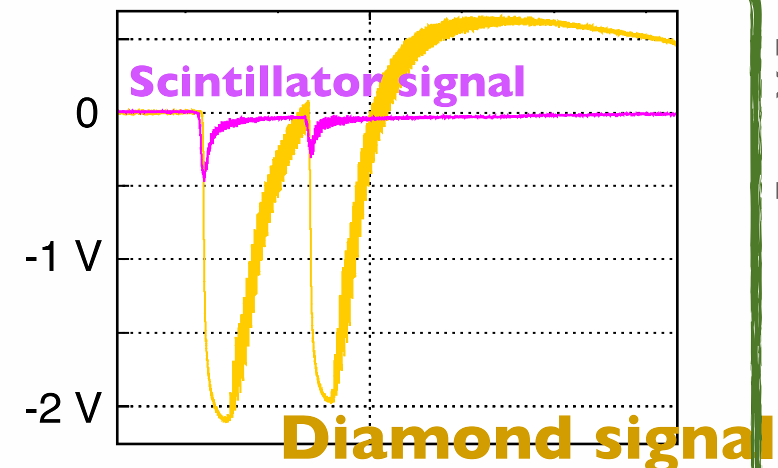
From Y. Fukao

Proton Monitor

Proton Beam Monitor

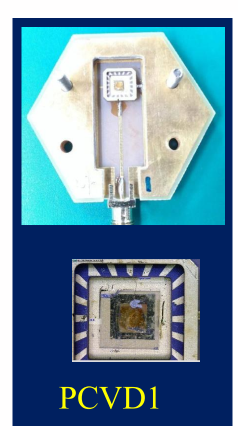
- Measure the proton beam profile and extinction.
- **Diamond semiconductors**
  - High radiation tolerance.
- Several prototypes have been developed.
- Tested at J-PARC MR abort line.
  - **Direct proton beam measurement also succeeded!**

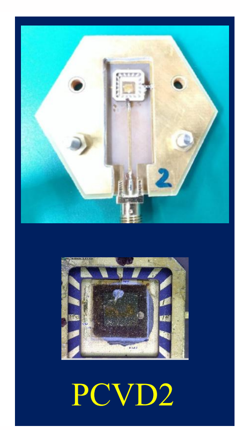


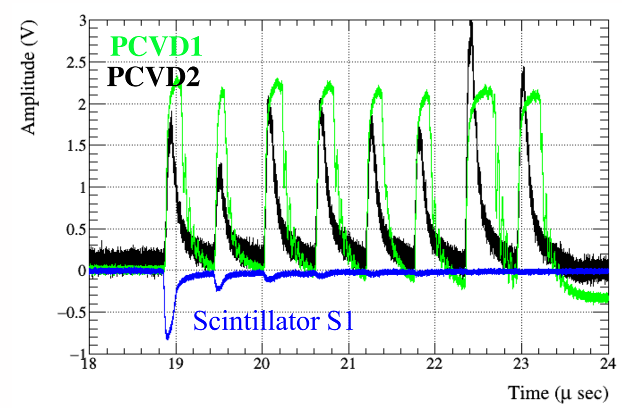


A diamond prototype located on-beam

From Y. Fujii







A diamond prototype located off-beam

From P. Sarin and H. Nishiguchi

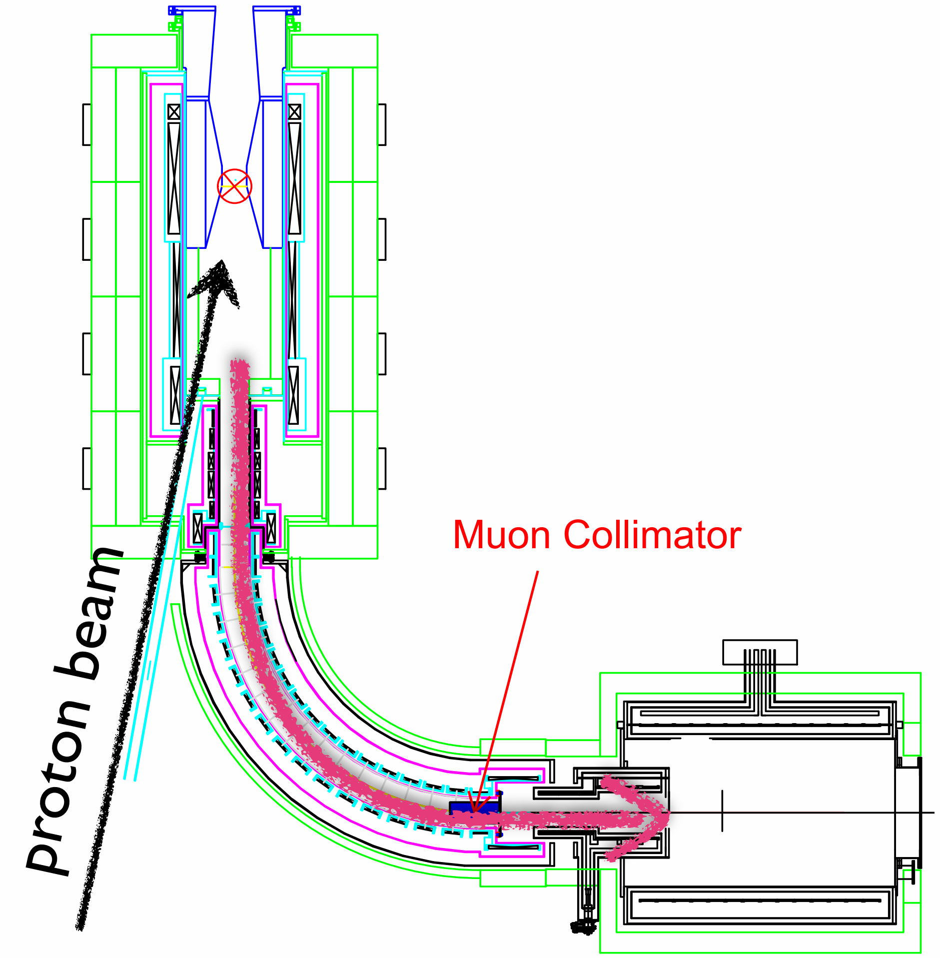
Proton to Stopped Muon (1)

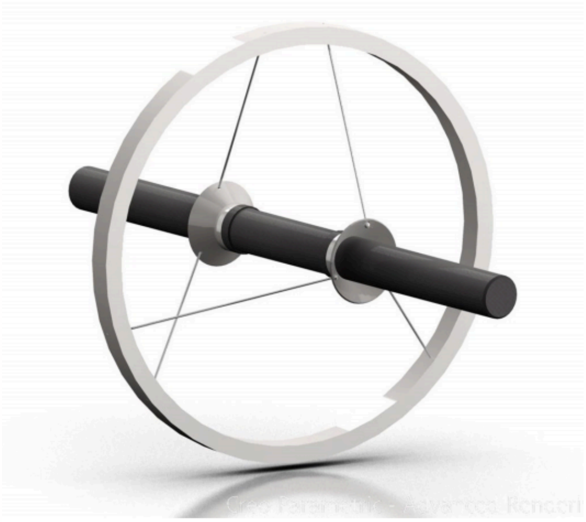
Proton Target

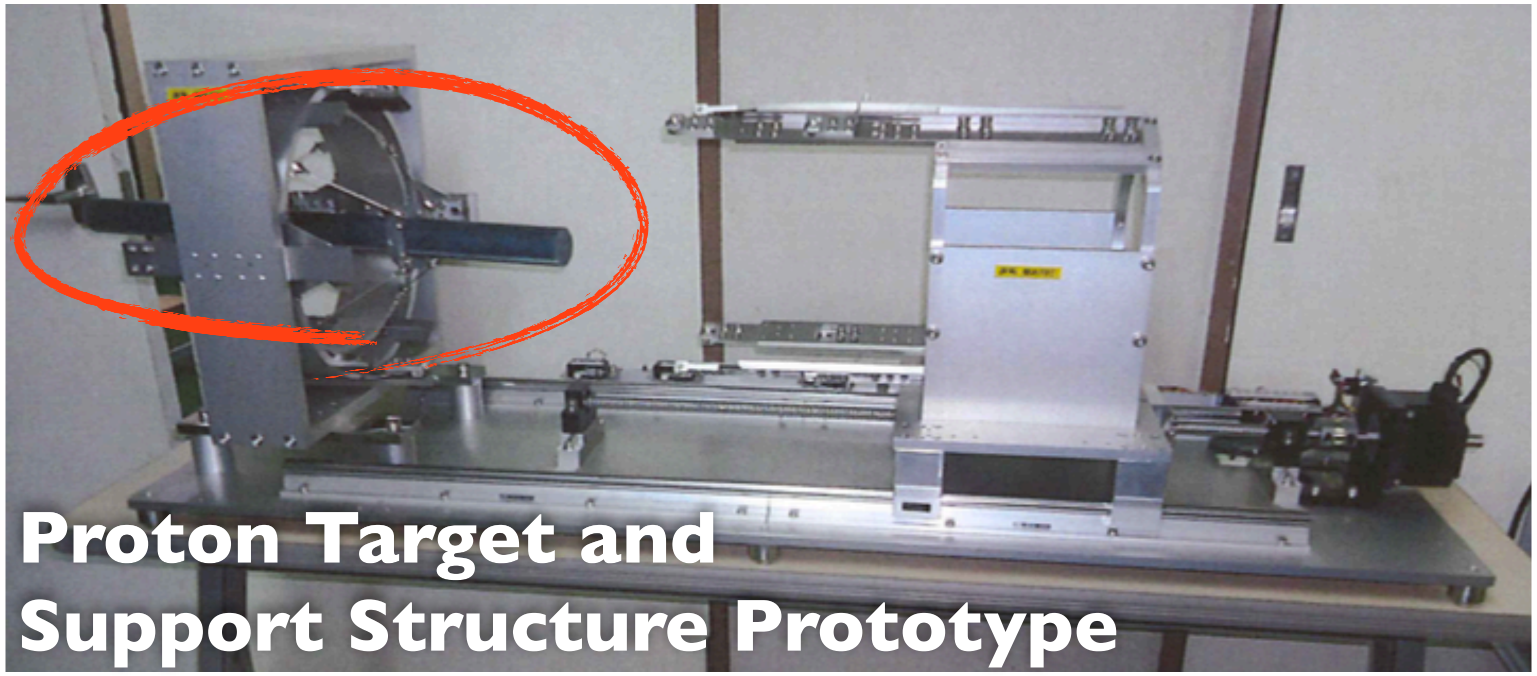
- Graphite (Tungsten) for Phase-I (II).
- SiC also under investigation.

Pion capture solenoid

- Pions are extracted to backward.
  - Better collection efficiency for low momentum pions.





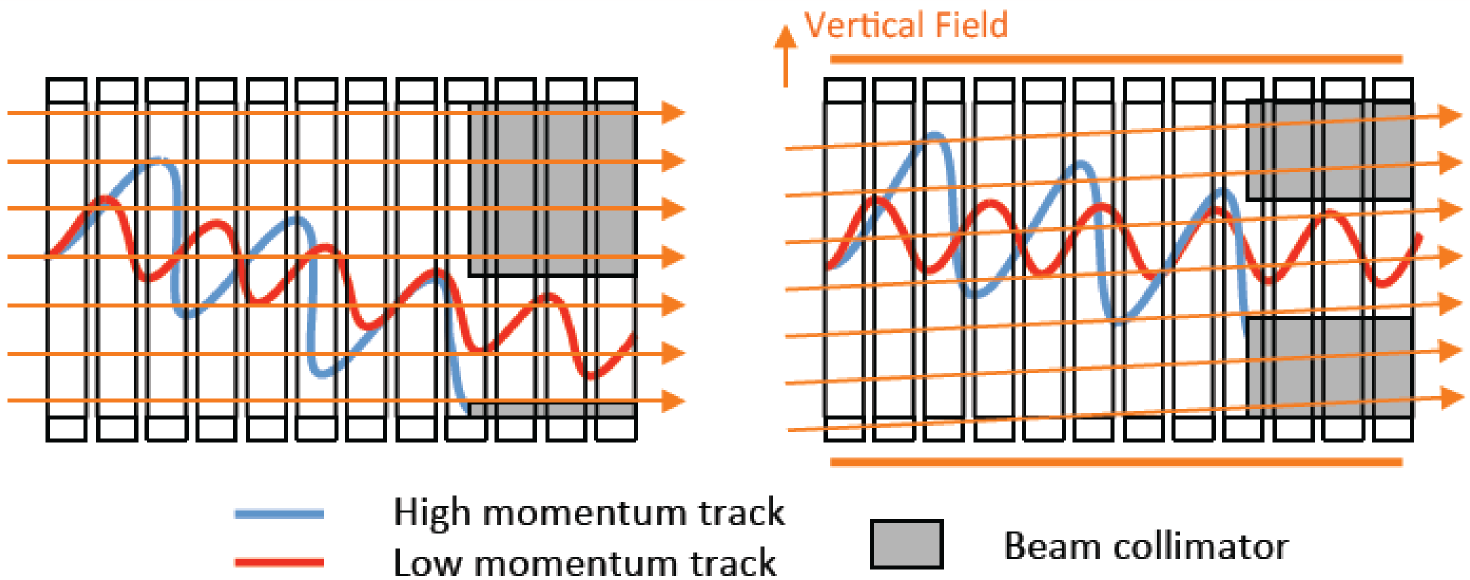


From S. Mihara

PROTON TO STOPPED MUON (2)

Muon Transport solenoid

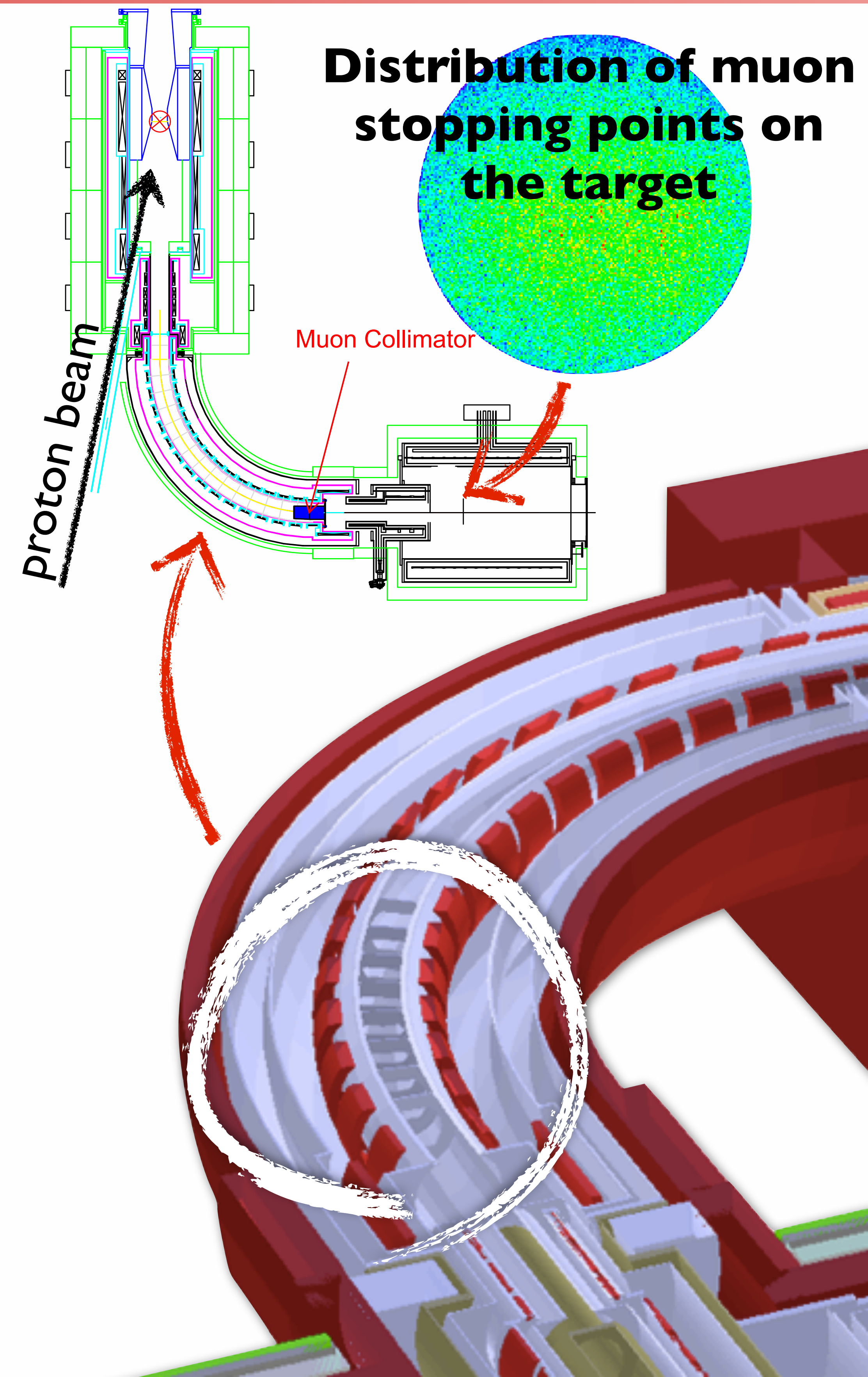
- Installation completed in 2015.
- Vertical magnetic field to compensate drifting of the center of helical trajectories.
  - Charge and momentum selection w/ optimized collimators



Trajectories in the transport solenoid

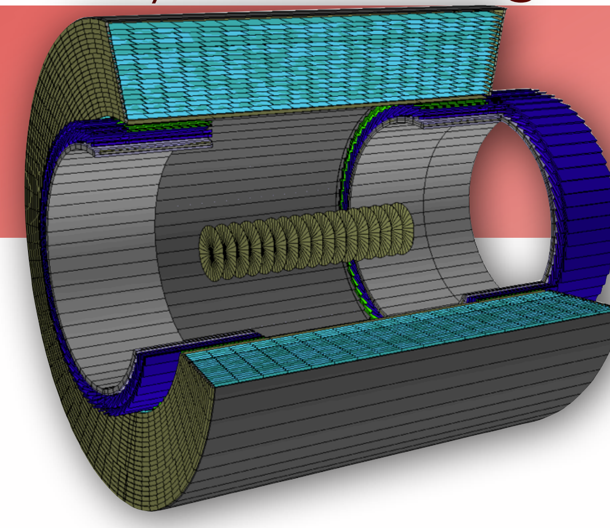
Al Muon Stopping Target

- 17 Flat disks
  - 10 cm radius, 200 µm thickness, and 50 mm spacing.
- 4.7×10^{-4} stopping muons / proton for Phase-I
  - Based on simulation study



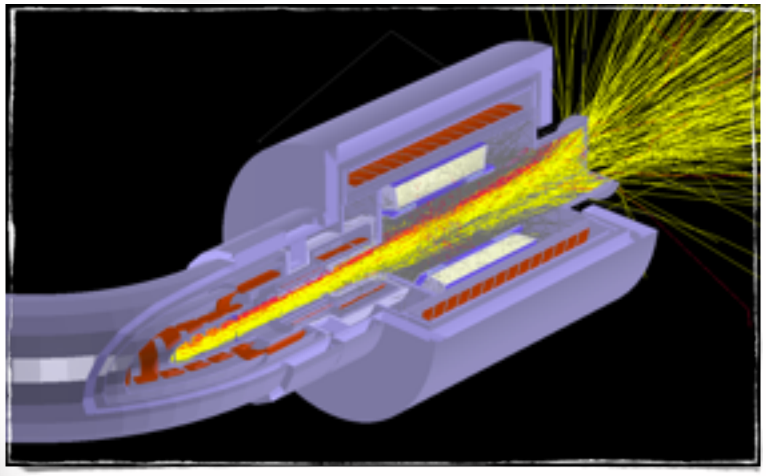
Detectors & Electronics

CDC (1)



Cylindrical Drift Chamber

- Measure signal electron momenta effectively, avoiding beam particles.
- 5000 (Au plated W) sense wires in 20 layers
  - Thanks to a stereo wire configuration, **3-dimensional position measurement is possible**.
- Chamber radius: 496 mm to 840 mm
  - Suppress hits by DIO electrons < 60 MeV/c
- **He(90): isobutane(10)** or **He(50):ethane(50)**
  - Both showed good performance in a beam test using a prototype.

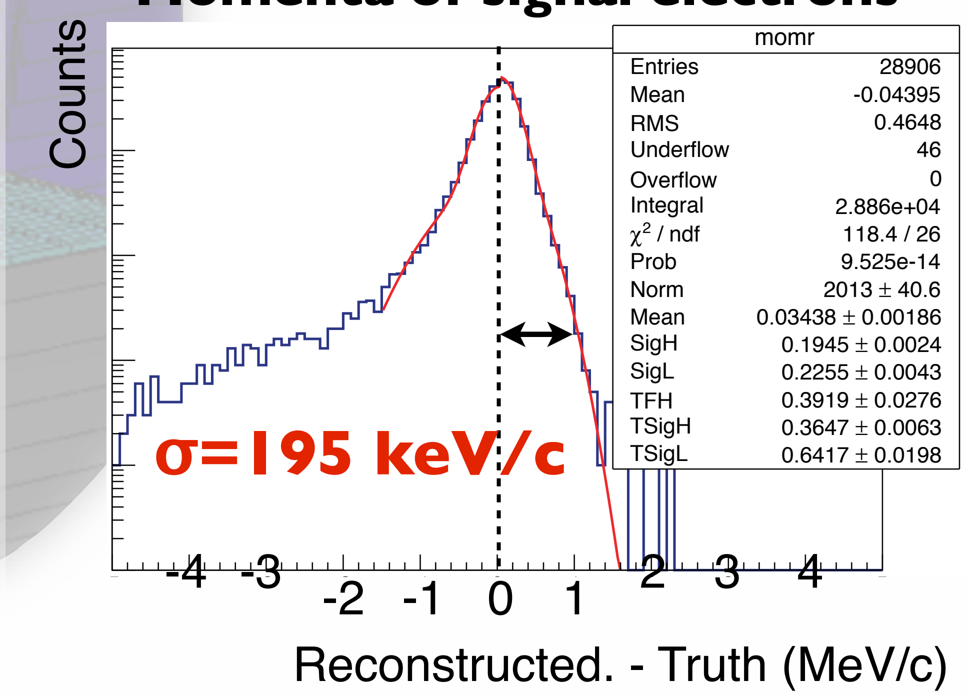


CDC and beam particles

Net performance based on simulation

- Optimized track finding and fitting for 105 MeV/c.
- Estimated a momentum resolution of **195** keV/c.

Momenta of signal electrons



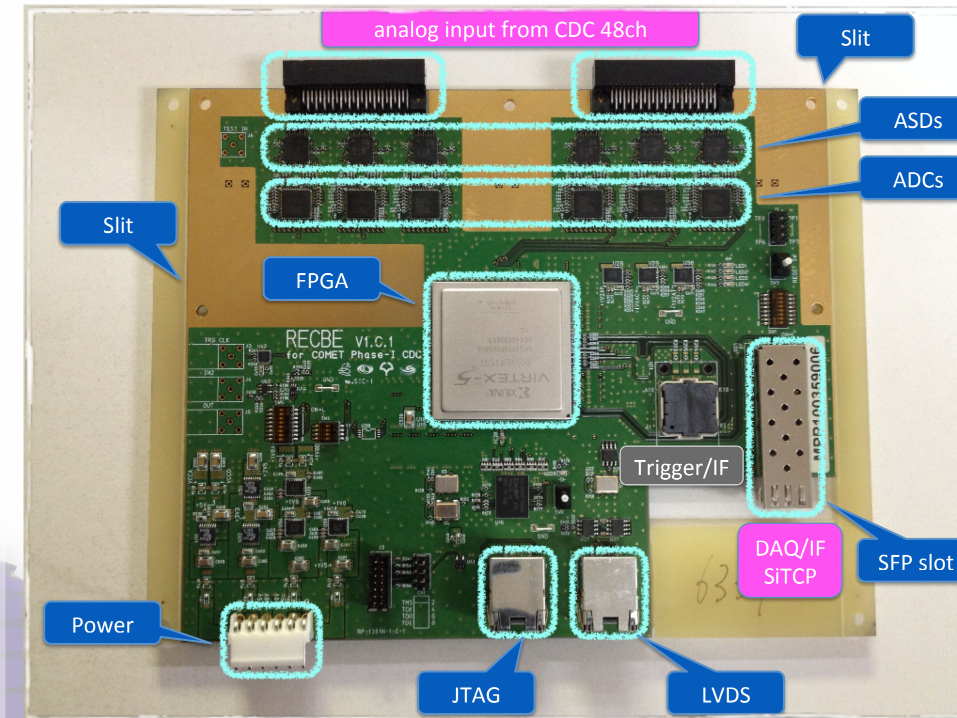
CDC (2)

Readout front-end electronics for CDC

- RECBE
- Mass production and test finished.

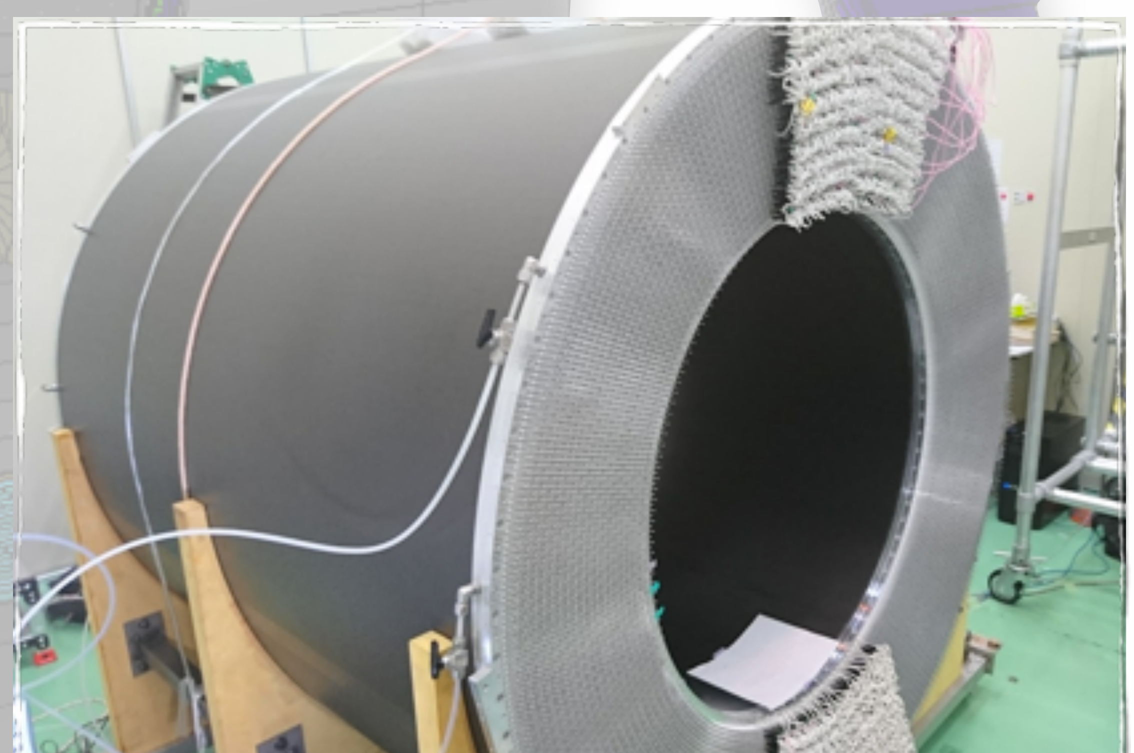
CDC Construction Completed in 2016

- Preparation of performance test using cosmic ray is ongoing.

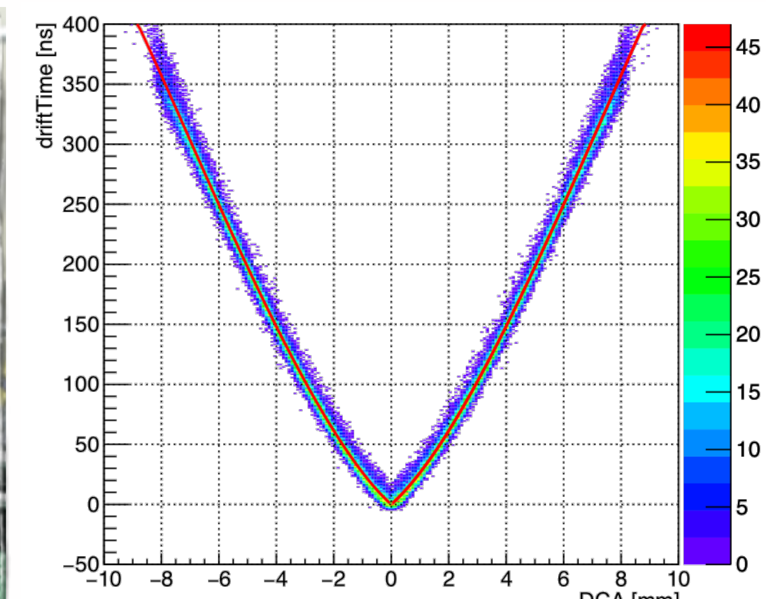


RECBE CDC readout front-end

Inside of CDC

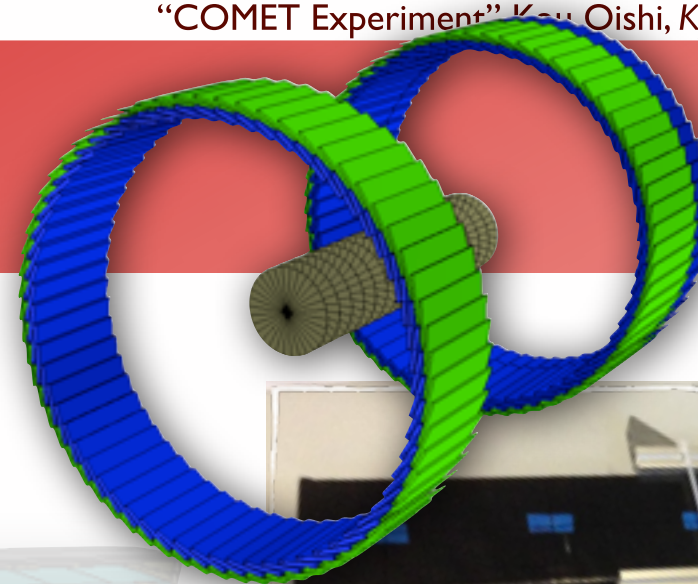


Constructed CDC



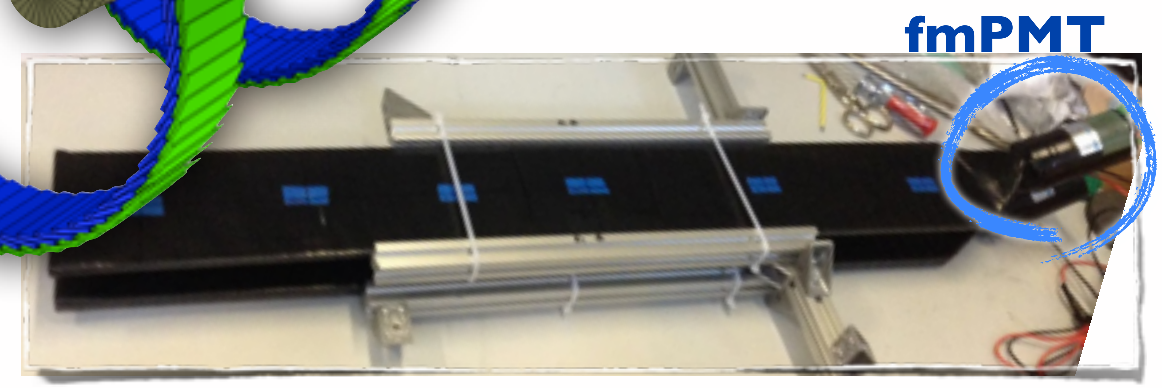
X-T curve reconstructed from pre-cosmic runs

CTH

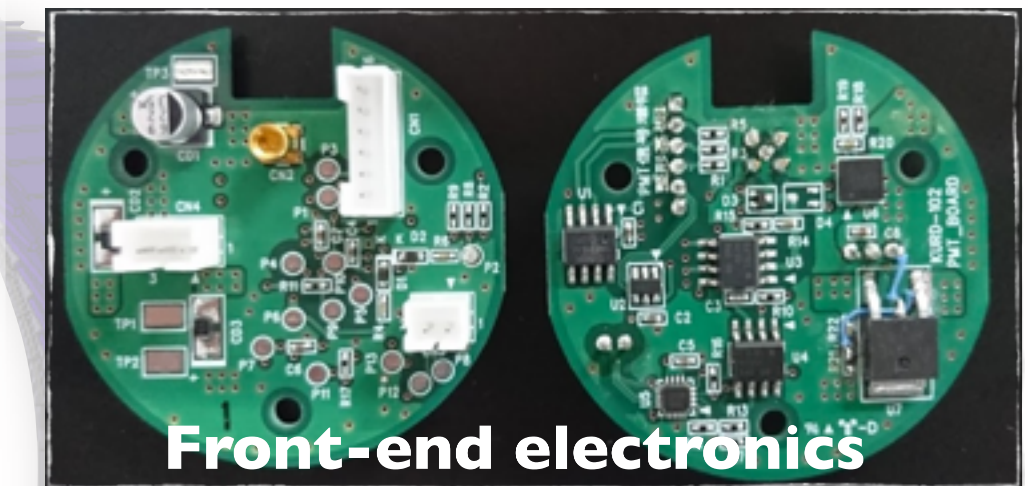


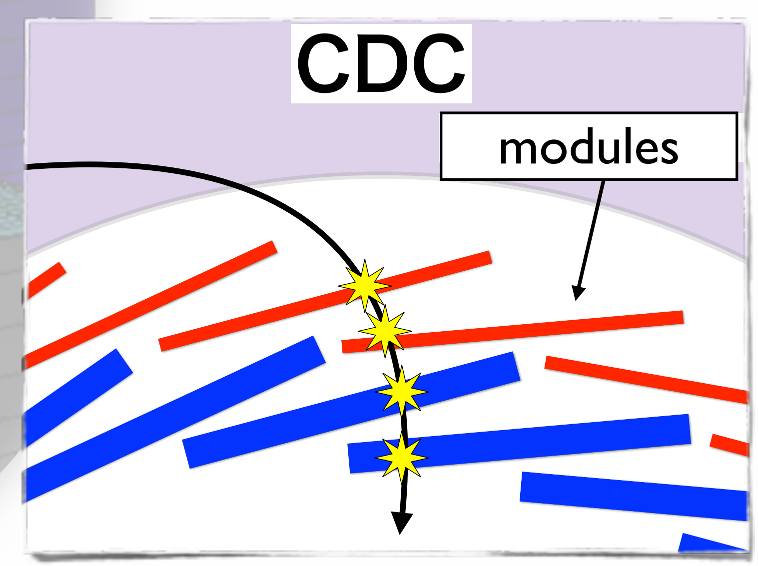
CyDet Trigger Hodoscope

- 2×48 segments installed at each end
  - (inner) **Acrylic Cherenkov radiator** for particle identification
  - (outer) **Plastic scintillator** for timing & position measurement
  - Readout by a fine-mesh type PMT + front-end electronics.
    - Functional under 1 T magnetic field.
  - Good performance shown in a beam test.
    - **S/N > 50** and **time resolution < 1 nsec.**
- For reasonable trigger rate,
  - Require 4-fold coincidence (2 for each)
  - Inner lead shield to block gamma rays from inside.



Radiator + scintillator prototypes



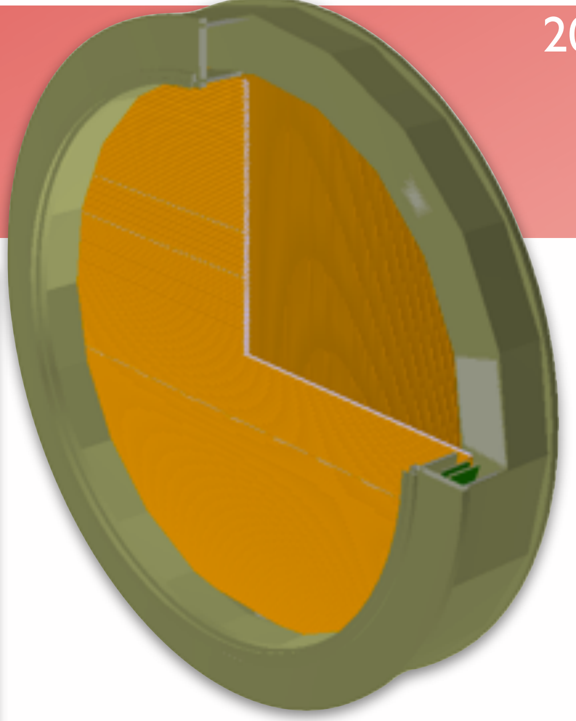


4-coincidence required

Straw Tracker

Thin-wall straw tube

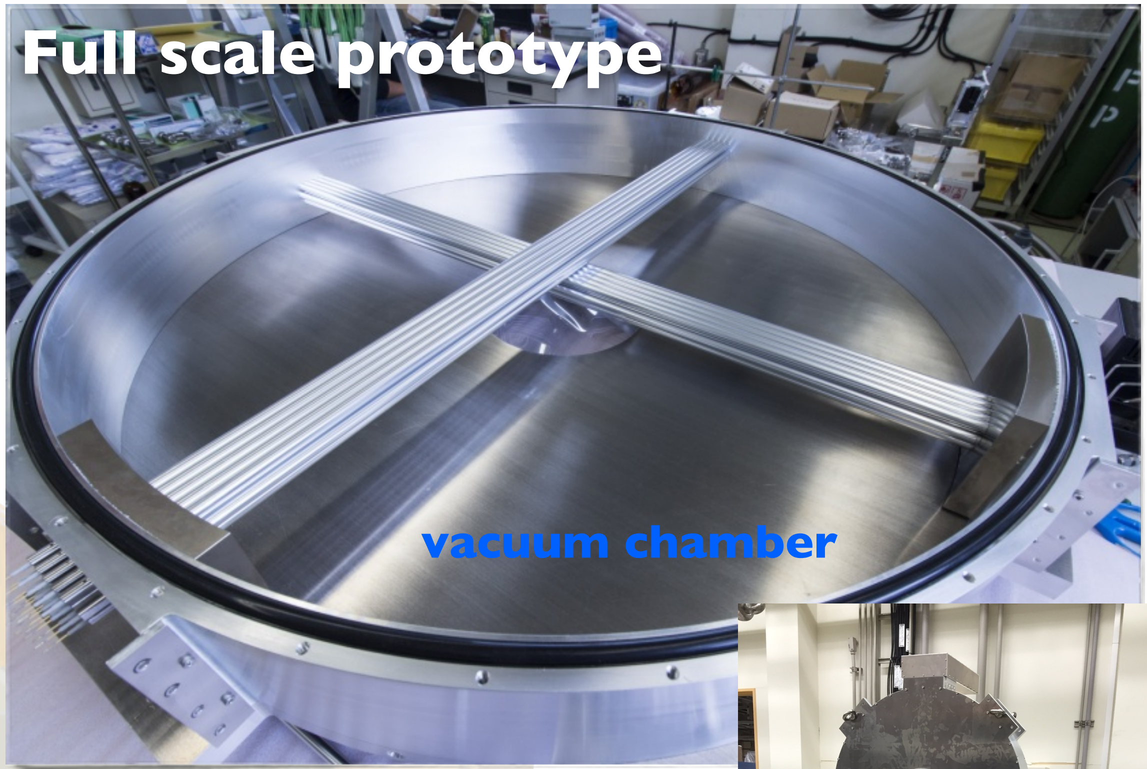
- 9.75 mmΦ straw with 20 μm thickness
  - Mass production of Phase-I straws completed.
  - 5 mmΦ w/ 12 μm in Phase-II
- **Ar(50):Ethane(50)** and **Ar(70):CO_2(30)**



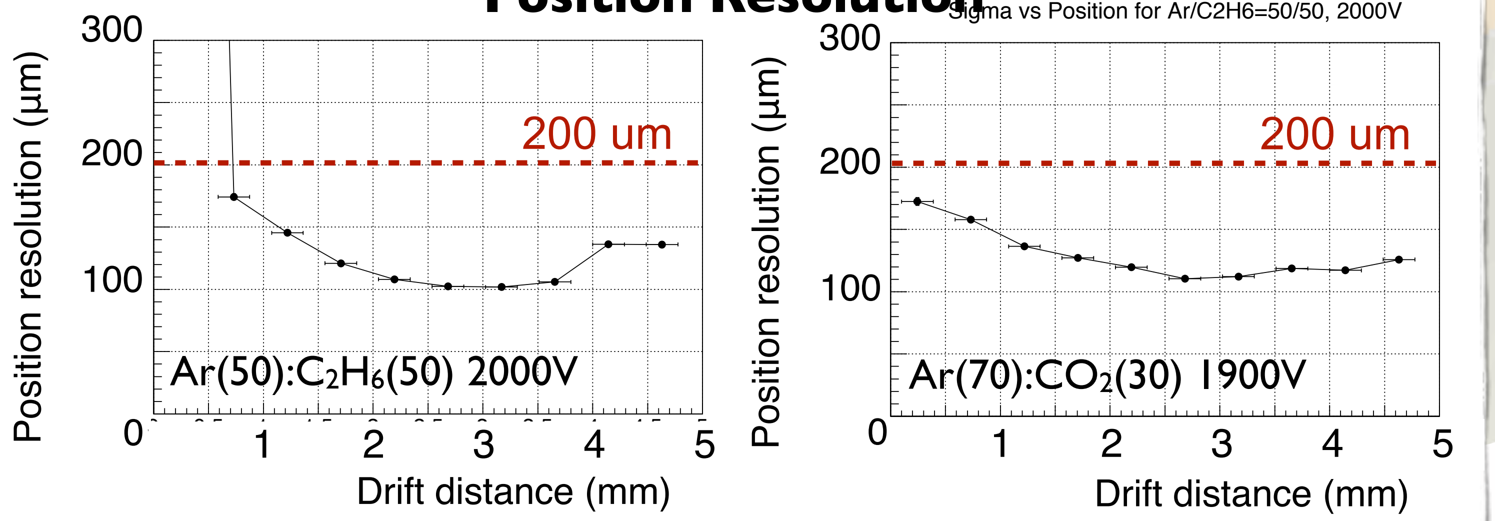
Straw station

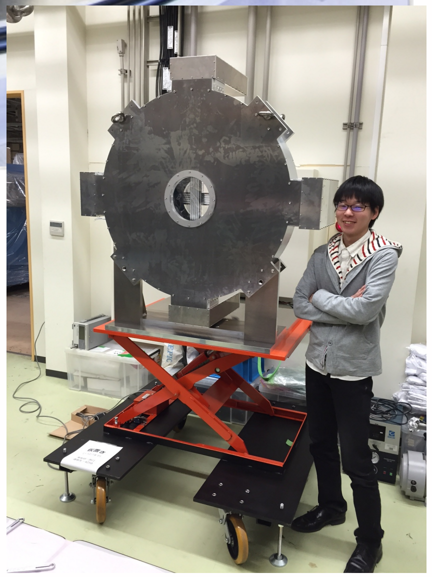
Full scale prototype w/ vacuum chamber

- Both showed **position resolutions < 200 um** in a beam test.
  - Momentum resolution < 200 keV is achievable.
- Succeeded operation in vacuum of < 0.1 Pa.
  - < 100 Pa required for the desired resolution.



Position Resolution





(standing up with a man)

ECAL

Requirement

- Particle identification for the beam measurement.
- Energy resolution < 5% required to suppress trigger rate of DIO electrons.

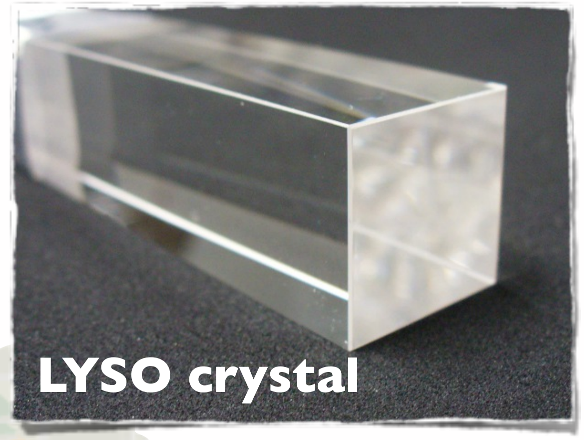
LYSO Crystal Scintillators

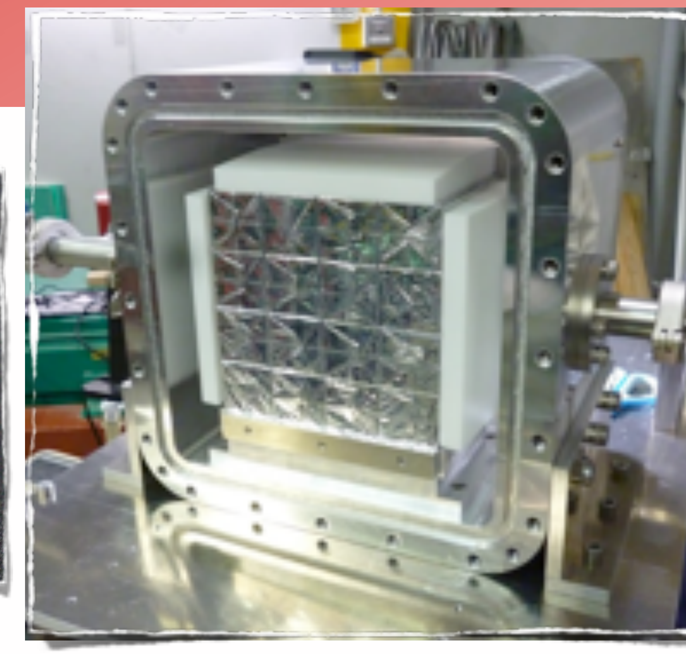
- high density (7.1 g/cm^3), high light yield (70% NaI), and fast time response (40 nsec)
- Dimension of 2 × 2 × 12 cm^3.
- Readout by 10×10 mm^2 APD + front-end electronics
- ~2000 crystals (~ 1 mΦ sensitive area.)

Prototype w/ 8×8 crystals

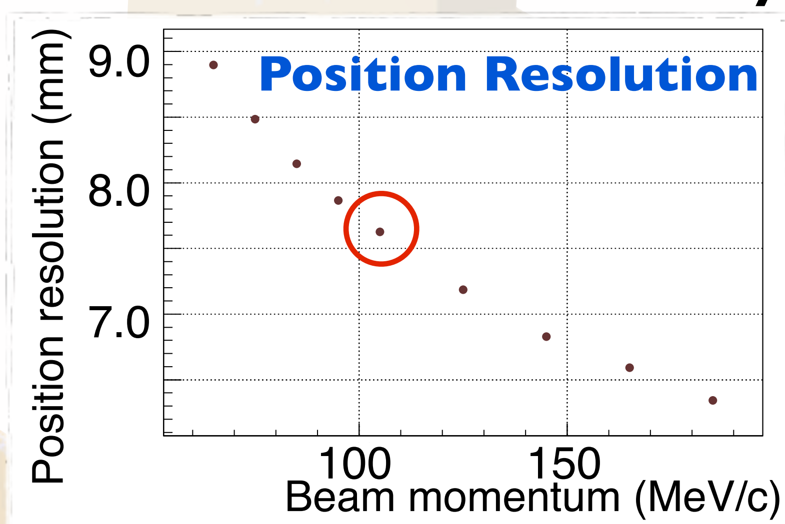
- Good performance at 105 MeV/c
  - **Energy resolution of 4.2%**
  - **Position resolution of 7.7 mm**
  - **Timing resolution of < 0.5 nsec**

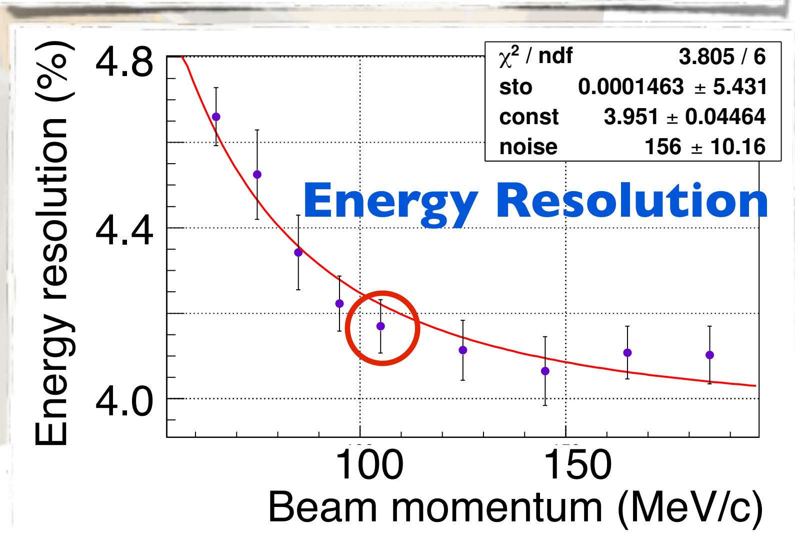
Kyushu Univ. leads the ECAL development.





ECAL prototype w/ 8×8 crystal modules

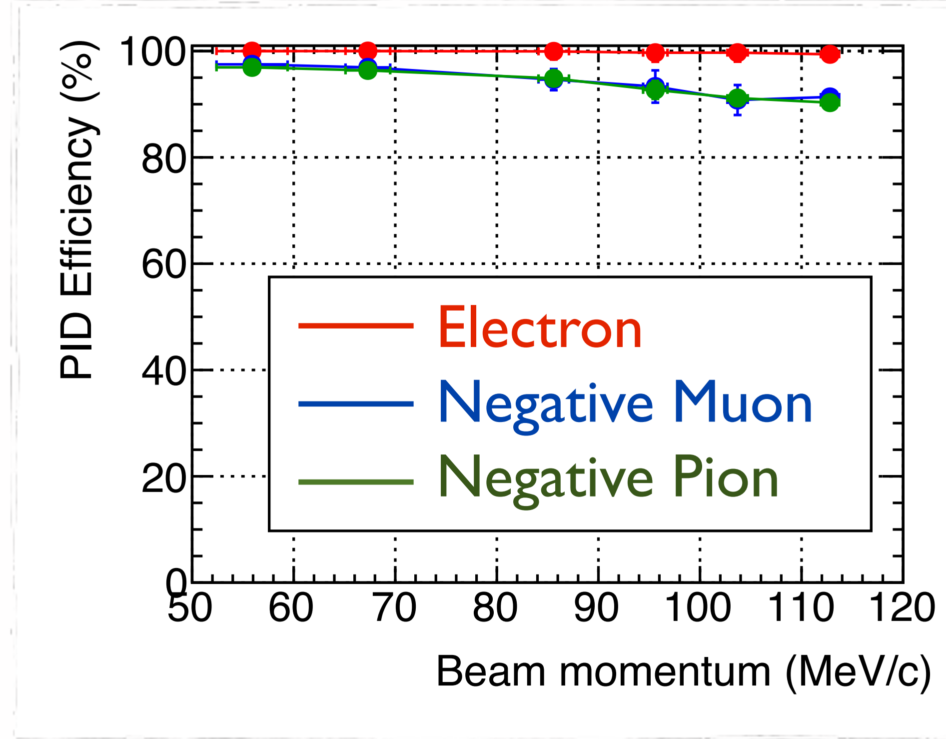




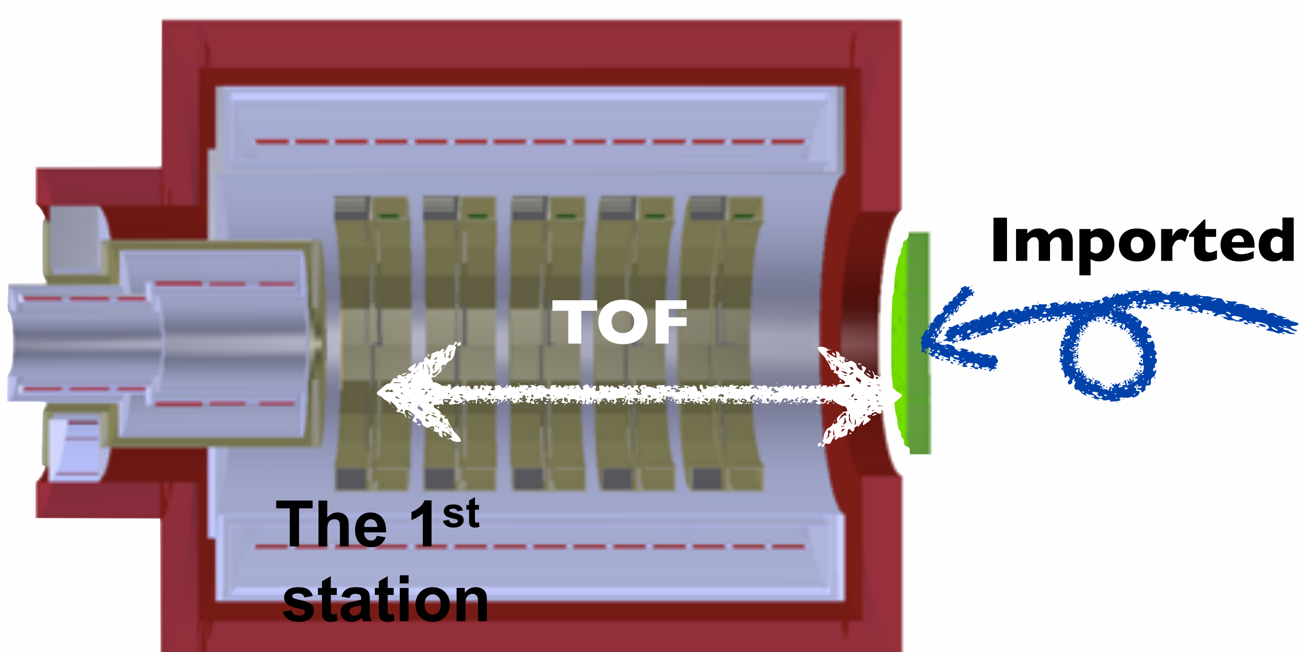
Particle ID w/ StrECAL

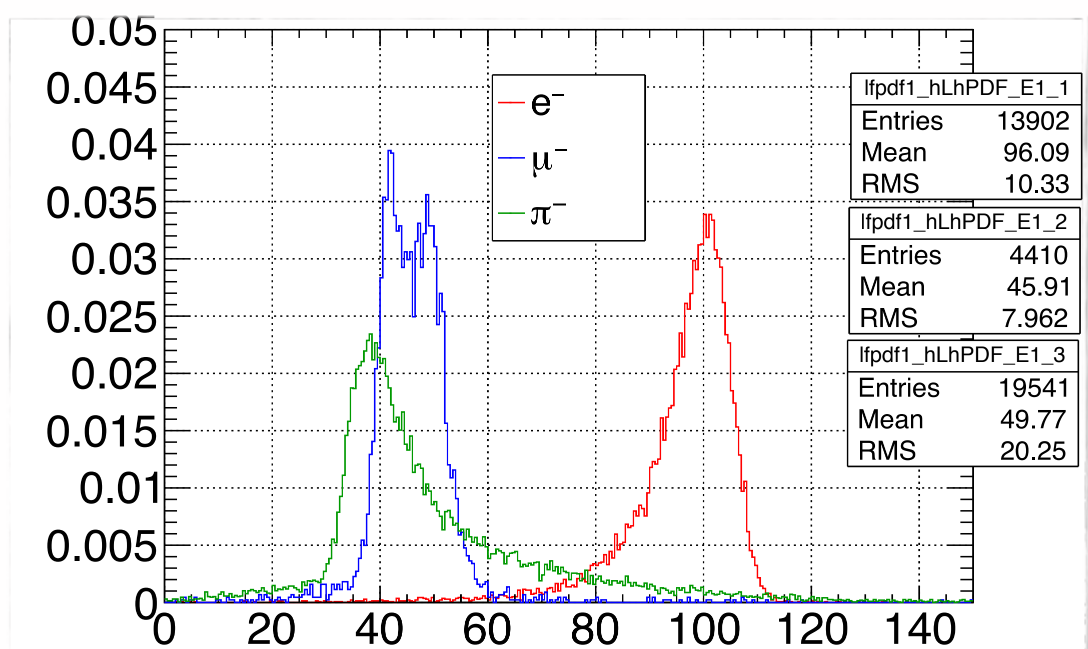
Particle Identification among e/μ/π

- Required to StrECAL for the beam measurement in Phase-I.
- A beam test was carried out to measure responses of each particle kind in the LYSO crystals.
- **PID efficiencies > 90%** for each of $e^-/\mu^-/\pi^-$ were evaluated.
  - Imported the experimental data of the ECAL response into simulation.
  - ECAL response is effective for high momentum region.
  - Time-of-flight information is effective for low momentum region.



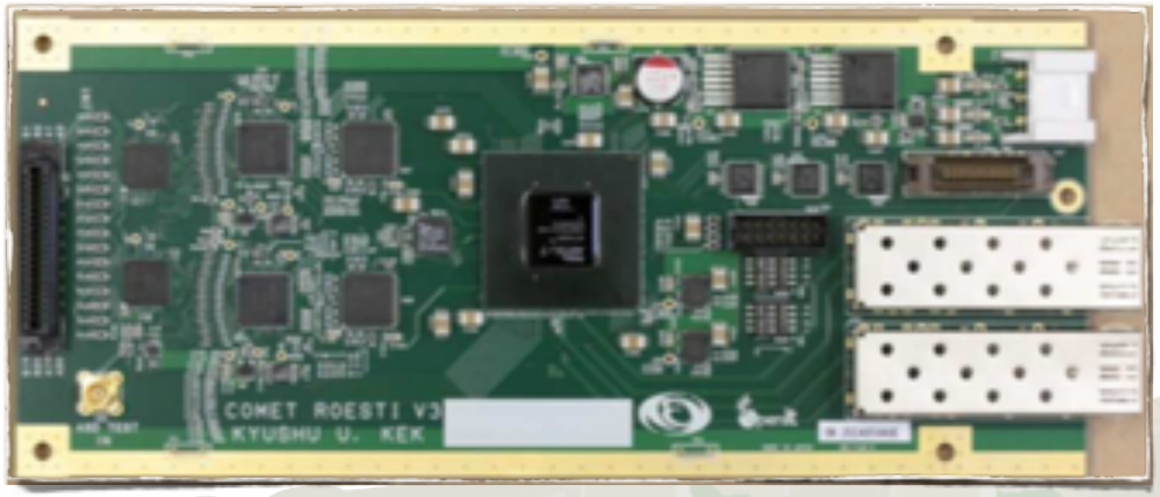
Estimated PID Efficiency





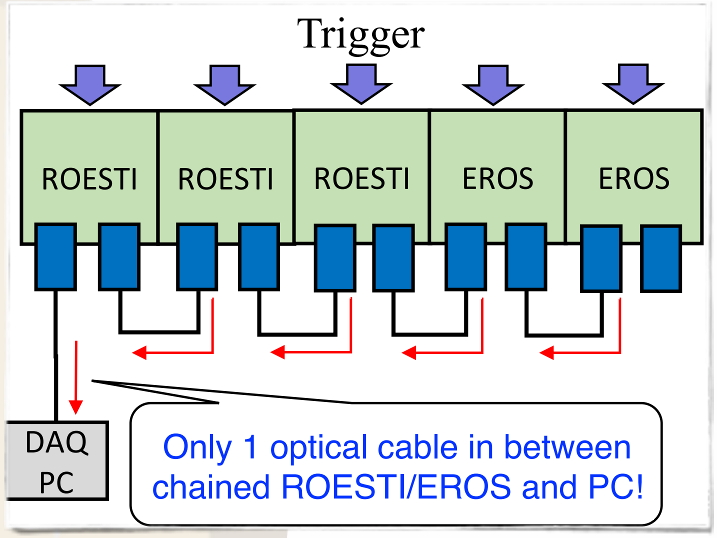
Experimental data of ECAL response.

StrECAL Electronics



ROESTI

EROS



Daisy-chained Readout

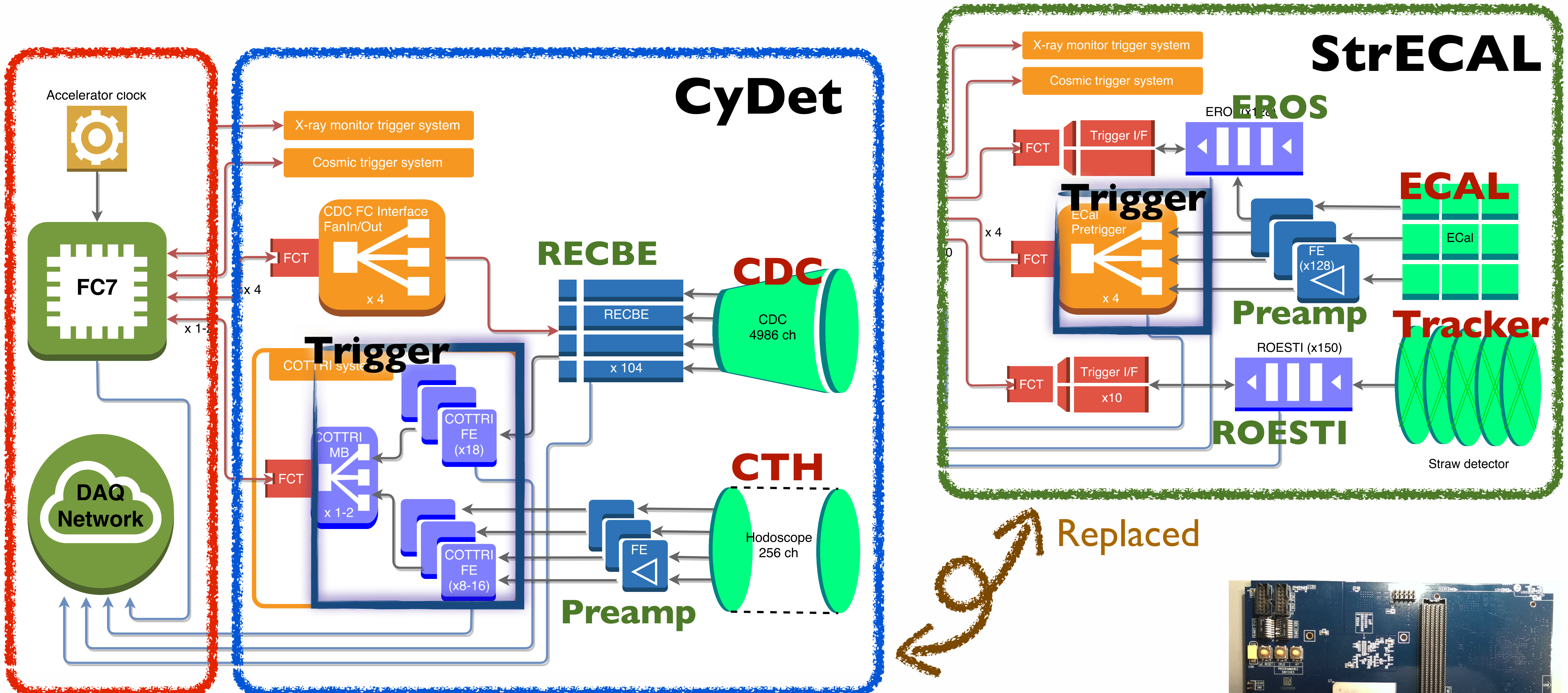
Readout electronics

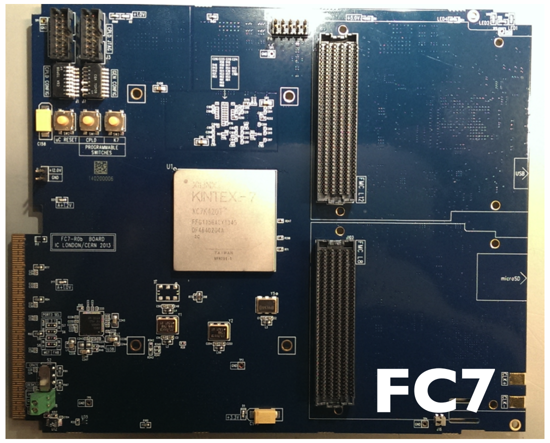
- Waveform-digitizing readout board
  - ROESTI (Straw Tracker) / EROS (ECAL)
  - Daisy-chained gigabit ethernet data transfer function.
    - To reduce the number of readout cables.

Trigger electronics

- **Pre-trigger / COTTRI**
  - Revisit these later.

TRIGGER



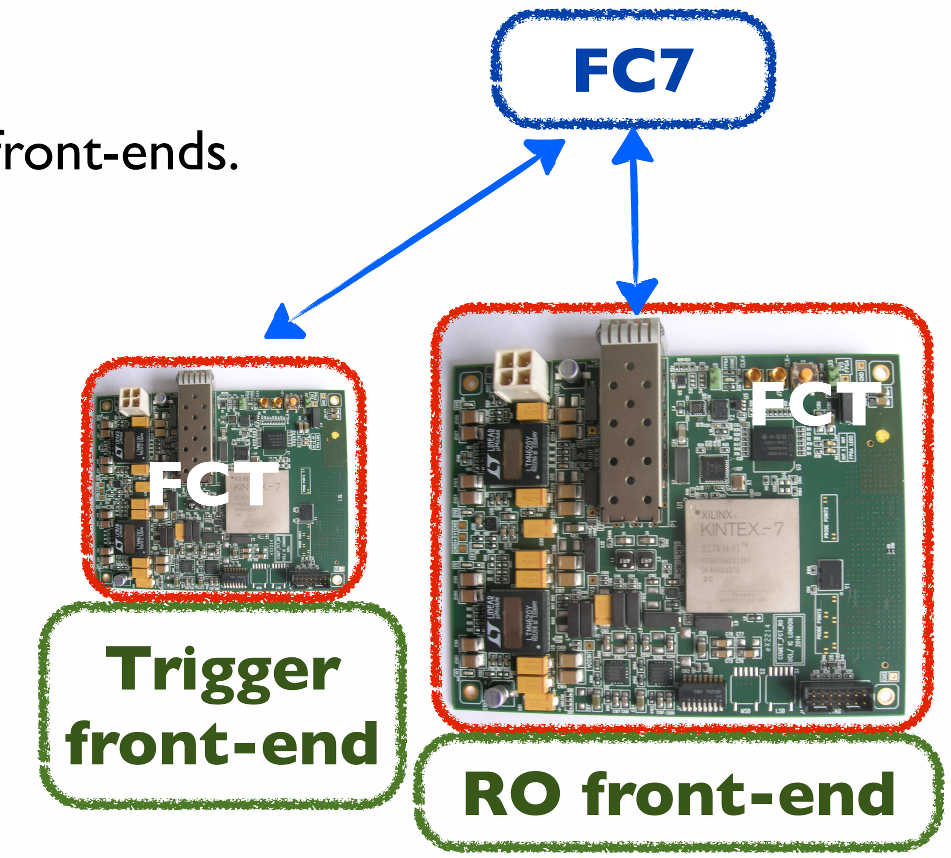


- A central board (FC7) administers trigger and readout.
  - Both the CyDet and StrECAL system can share it.
- **FC7**: general use FPGA board supporting gigabit data transfer (developed by CMS@CERN).
  - Clock distribution and fast control based on **GBT** (Gigabit transceiver) protocol.

Trigger (2)

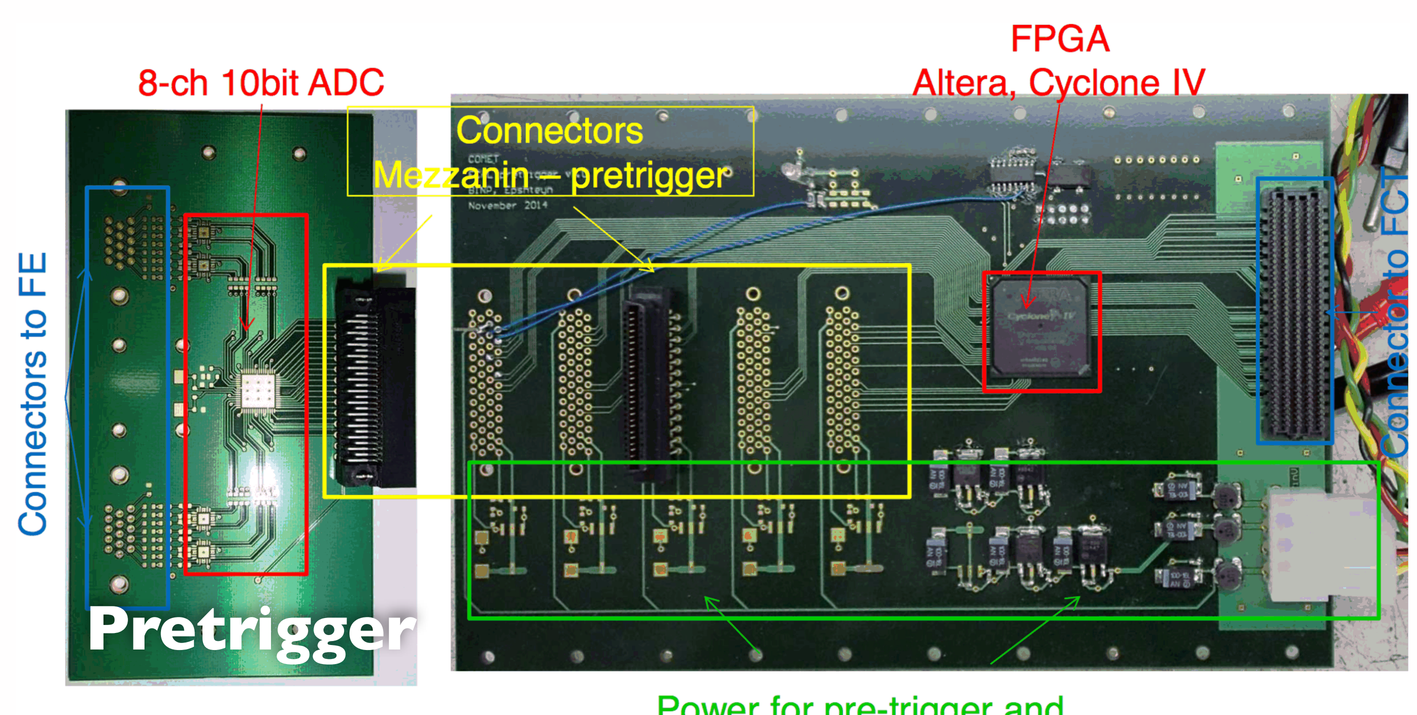
FCT: Fast control and timing board

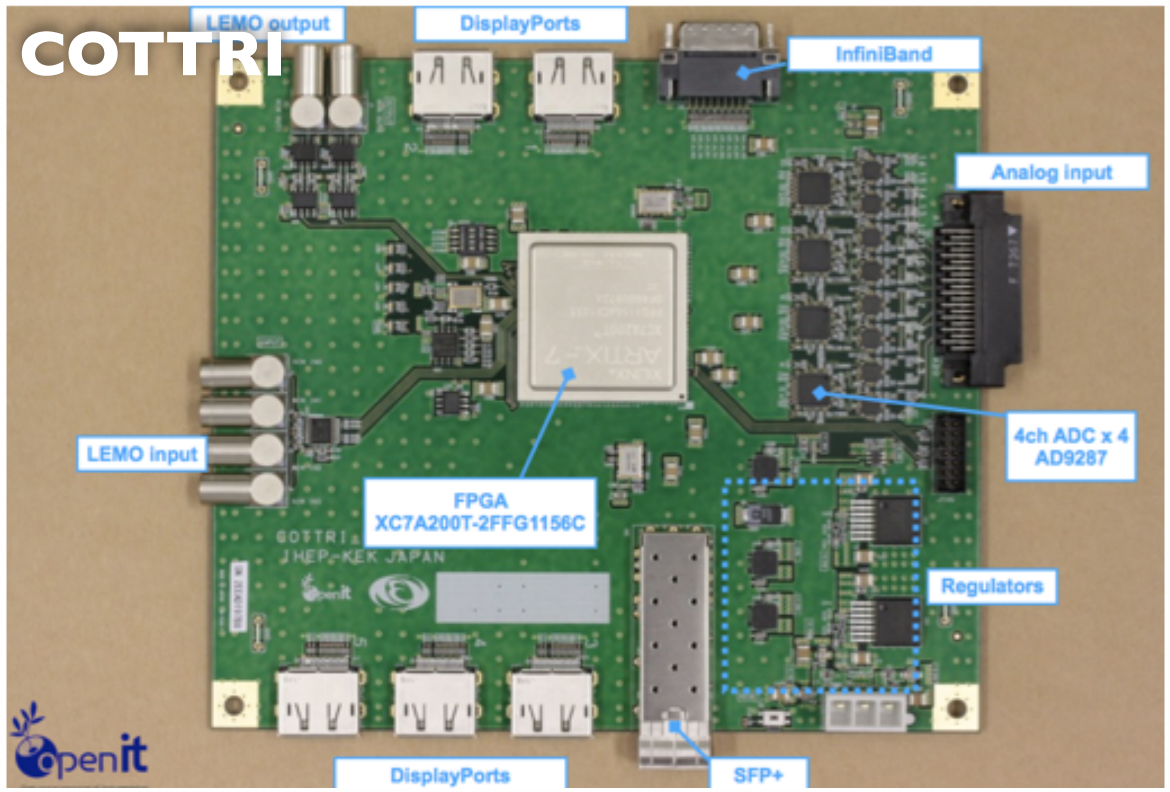
- Interface between FC7 and subdetector specific trigger / readout front-ends.
  - information from the trigger board to FC7 for trigger decision.
  - trigger signal from FC7 to the front-ends.



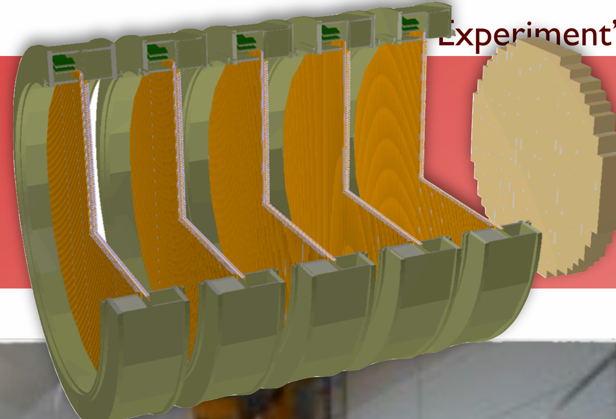
Detector-specific Trigger Front-ends.

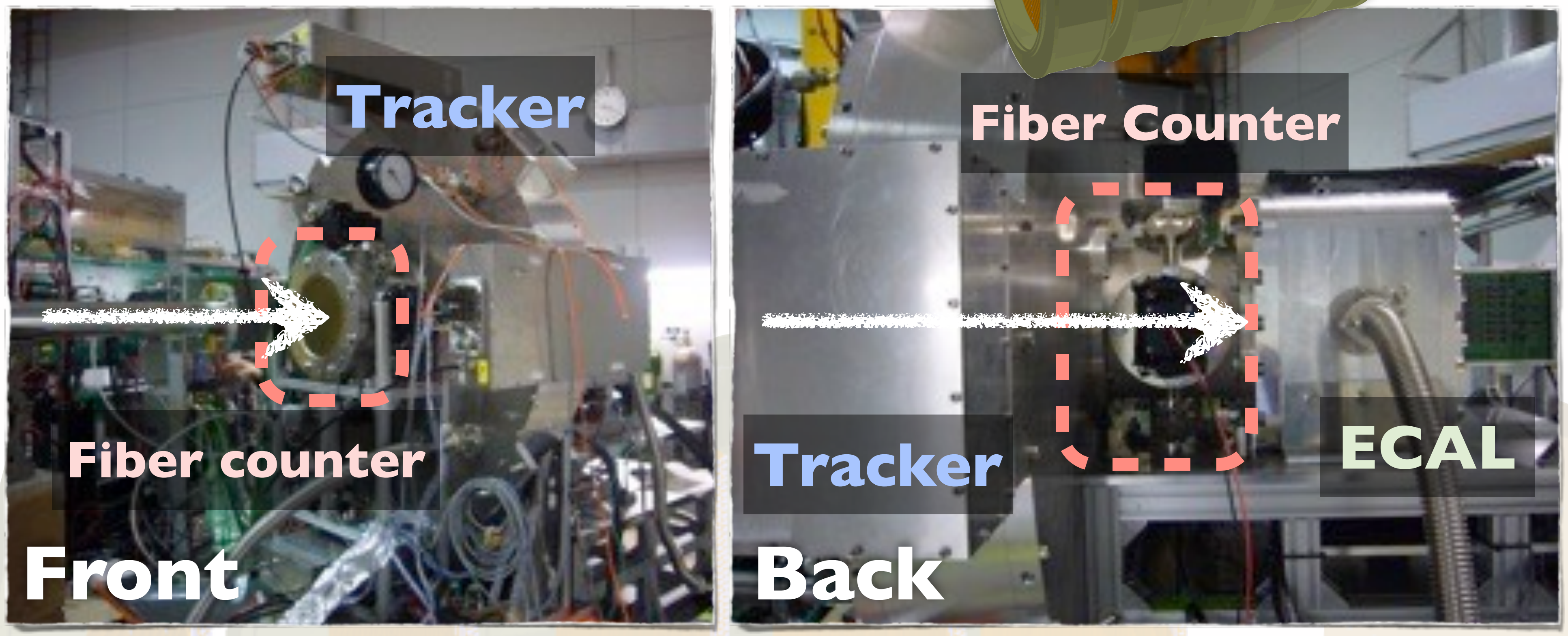
- **COTTRI**: CyDet trigger front-end
  - Trigger decision from CDC and CTH signals.
    - Applicable to StrECAL, too.
- **Pretrigger**: StrECAL trigger front-end
  - Sum up energies and send it to FC7 for the trigger decision.





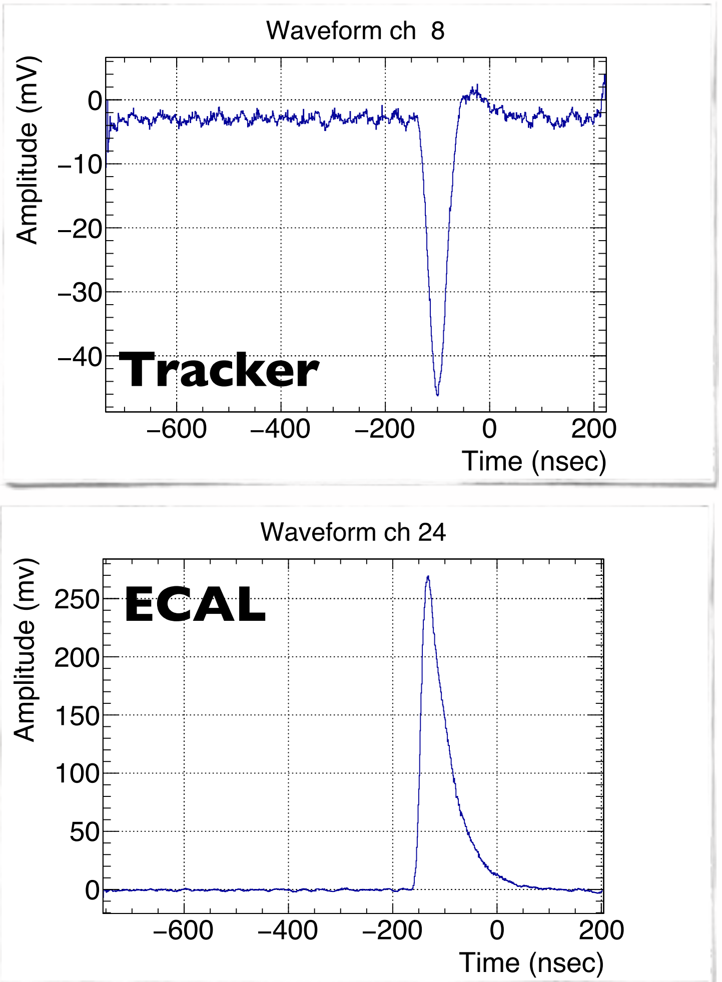
StrECAL



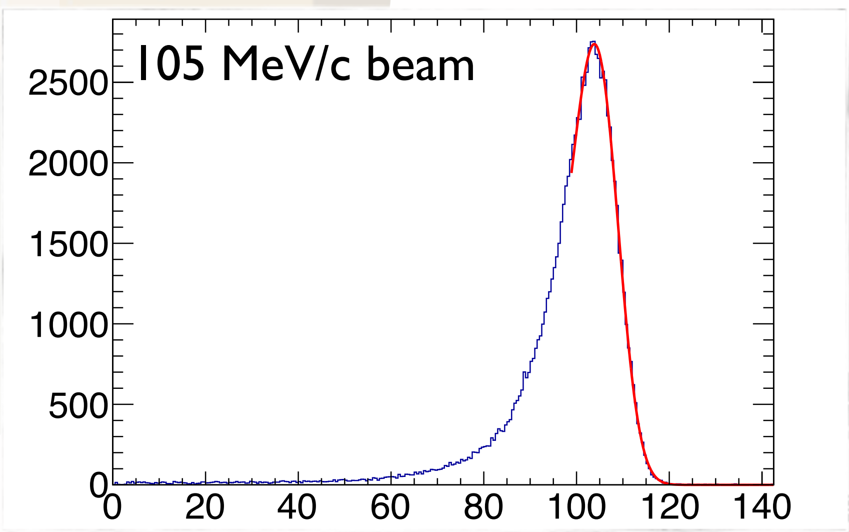


Combined StrECAL Beam Test (Mar. 2017) at Tohoku Univ., Japan.

- ✦ Combined the final prototypes of the tracker and ECAL.
  - ★ Data analysis is ongoing.
- ✦ Tested the front-end electronics and trigger system, too.



Waveforms



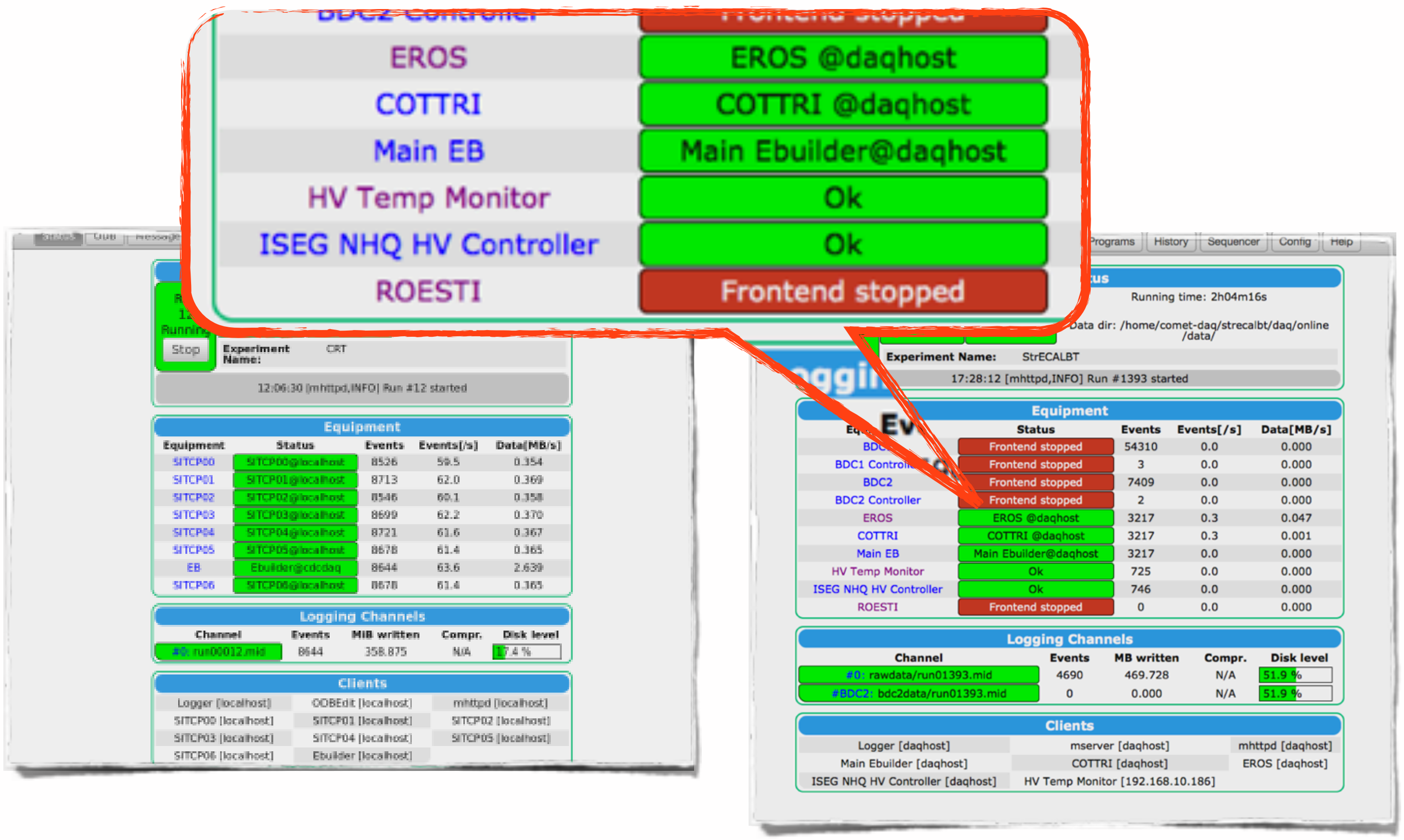
Energy Distribution of ECAL

COMET

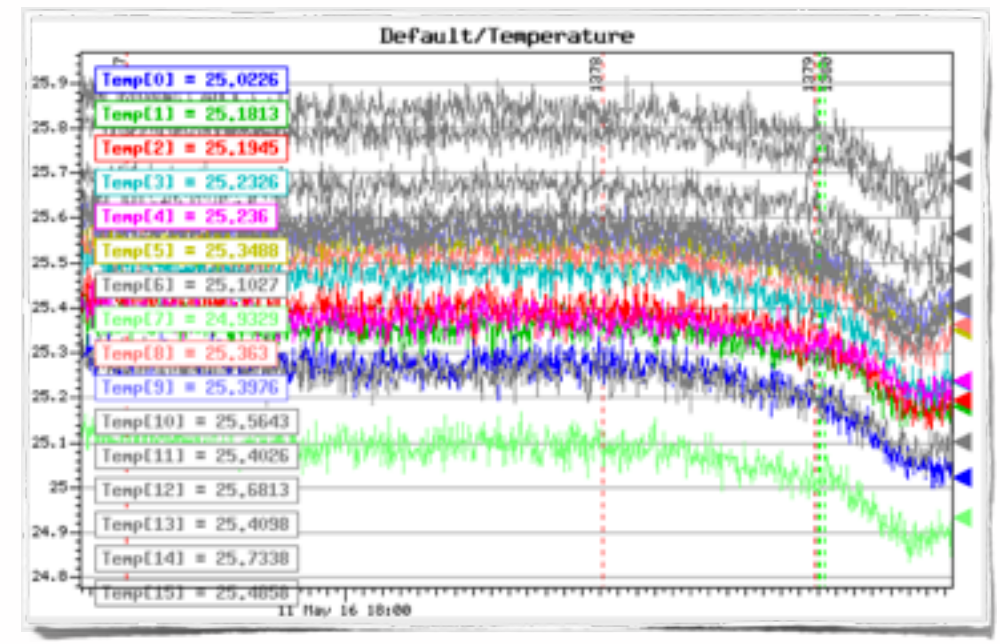
μ e

SOFTWARES

DAQ Software



DAQ Prototypes for CyDet and StrECAL

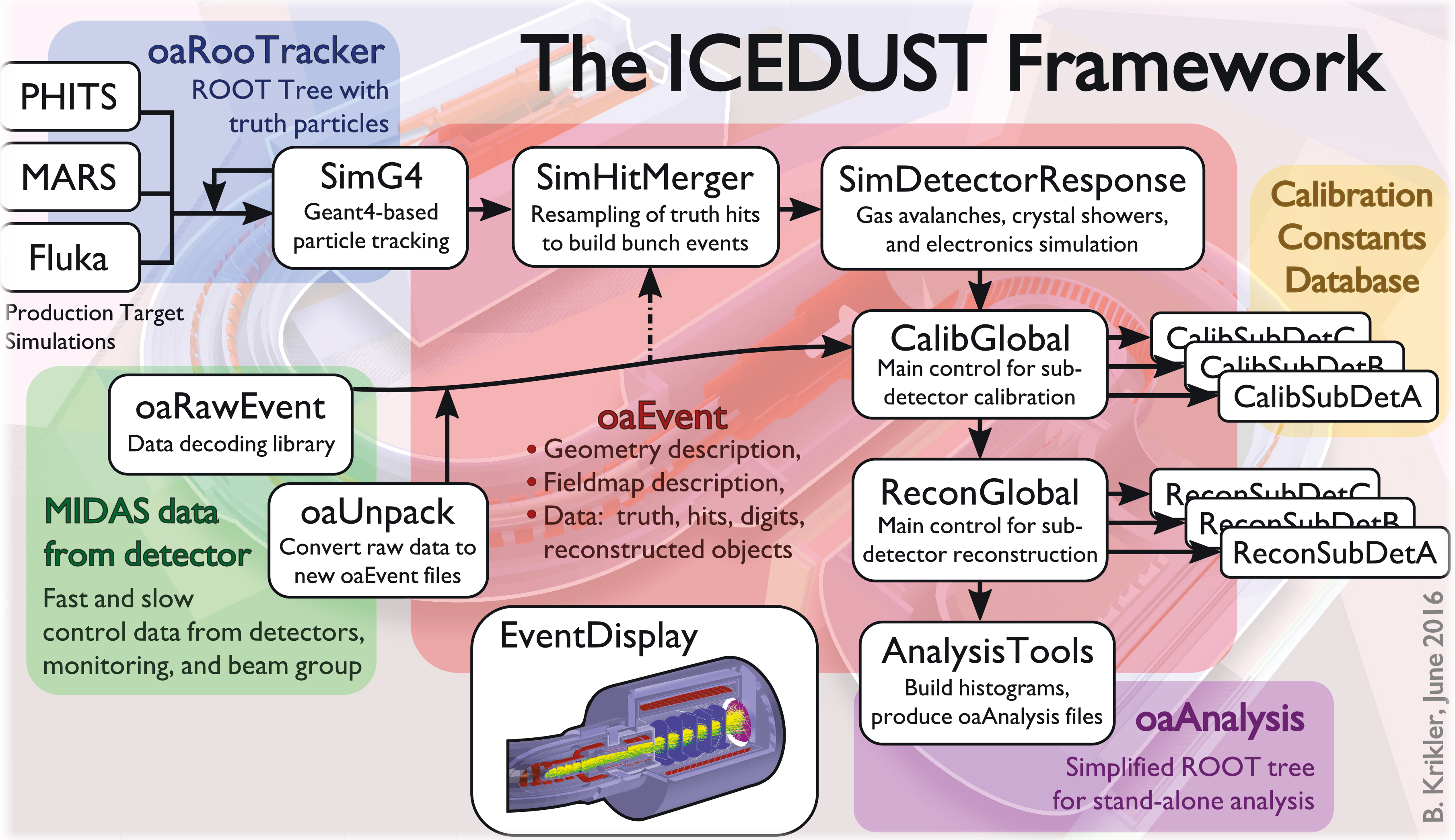


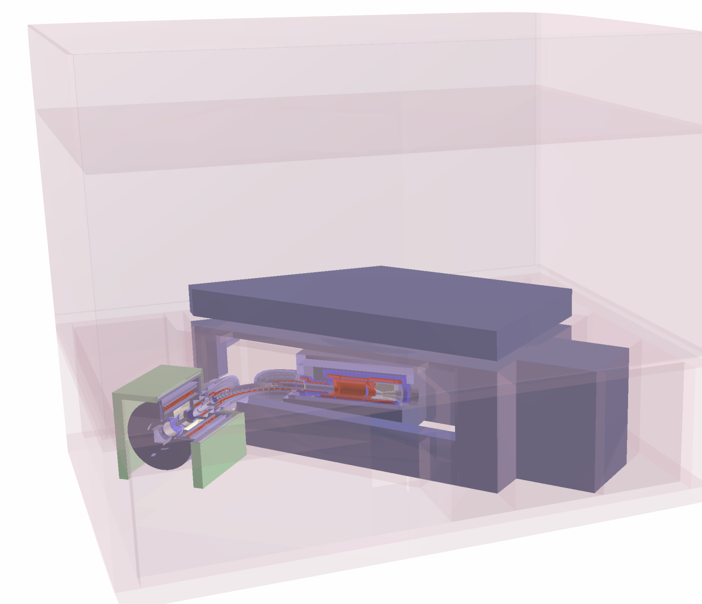
History of Monitored Temperatures around the ECAL.

DAQ Software Based on The MIDAS Framework

- ✦ MIDAS has been used for the MEG, T2K ND280, etc.
- ✦ Include slow control operation & history function.
- ✦ Prototypes have been developed for the CyDet and StrECAL.
  - ★ Demonstrated in lab. tests and beam tests.

Offline Software





Full Geometry of Phase-I in the Simulation software (SimG4)

COMET Offline Software Framework ICEDUST

- ★ A derivation from the framework for the ND280 detector of the T2K experiment.

- ✦ Full physic&detector simulation, geometry&magnetic field handling
- ✦ Unified data structure for both simulated and experimental data.
- ✦ Calibration, reconstruction, and analyzer packages.

COMET

Sensitivity and Backgrounds

Phase-I Sensitivity

Single Event Sensitivity (SES)

- Estimated **3×10^{-15}** for 150 days operation.

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}} = 3\times10^{-15} \quad \text{(as SES)}$$

- ★ **$N_\mu = 1.5\times10^{16}$** : the number of muons stopped in the target
- ★ **$f_{cap} = 0.61$** : The fraction of captured muons to total muons on target
- ★ **$f_{gnd} = 0.9$** : the fraction of μ-e conversion to the ground state in the final state
- ★ **$A_{\mu\text{-}e} = 0.041$** : the net acceptance for the μ-e conversion signal (see below)

Event selection	Value	Comments
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	$103.6\ \mathrm{MeV}/c < P_e < 106.0\ \mathrm{MeV}/c$
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3	$700\ \mathrm{ns} < t < 1170\ \mathrm{ns}$
Total	0.041	

Phase-I Backgrounds

Four categories of the backgrounds

- "Prompt beam" and "delayed beam" ones will be directly evaluated in the beam measurement of Phase-I.

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.

NOTE) Supposed the extinction = 3×10^{-11}

Phase-II Sensitivity

SES 1.9 $\times 10^{-17}$

- ★ 2/3 year running
- ★ for comparison with Mu2e.

✦ **$N_\mu = 1.5\times10^{18}$**

- ★ 2.1×10^{-3} stopping muon/proton
  - ❖ 4.7×10^{-4} (Phase-I)

✦ **$A_{\mu\text{-}e} = 0.057$**

- ★ Improved with a lot of optimization on the acceptance.
  - ❖ 0.041 (Phase-I)

✦ Background is 0.34.

✦ The study is still ongoing.

Preliminary

	Single event sensitivity	Total POT ($\times10^{19}$)	Beam time t_{run} (s)	SES in one year of continuous beam
COMET Phase-II (this study)	2.6×10^{-17}	68.3	1.57×10^{7}	1.29×10^{-17}
COMET Phase-II (CDR 2009 [45])	2.6×10^{-17}	85	2.00×10^{7}	1.65×10^{-17}

old estimation

Overall Acceptance	2009 CDR [45]	This Study
Geometric acceptance	0.20	0.22
Solid angle with mirroring	*(0.73)*	
Beam blocker acceptance	*(0.57)*	
Spectrometer acceptance	*(0.47)*	
Timing window efficiency	0.39	0.53
Momentum cut efficiency	0.72	0.70
TDAQ acceptance and efficiency	0.90	N/A
Reconstruction aspects	0.78	N/A
Recon. efficiency	*(0.88)*	
Track quality cut efficiency	*(0.89)*	
Additional analysis cuts	0.81	N/A
Transverse momentum cut efficiency	*(0.83)*	
E/p cut efficiency	*(0.99)*	
Pitch angle cut efficiency	*(0.99)*	
Total acceptance at 'truth level'	0.056	0.091
Total (with CDR recon. and TDAQ efficiencies)	0.039	0.057

From PhD thesis by Ben Krikler

SUMMARY

Summary & Schedule

COMET experiment will search for μ-e conversion in two phases at J-PARC.

- Aims at sensitivity of $<10^{-14}$ and $<10^{-16}$ for Phase-I and Phase-II, respectively.
- Perform a direct measurement of the beam profile and backgrounds in Phase-I.
- The facility is under construction.
- R&D of the detectors, CyDet & StrECAL, is progressing.
- Single event sensitivity: 3×10^{-15} (Phase-I) and 1.9×10^{-17} (Phase-II).