COMET experiment

search for muon to electron conversion

Hisataka Yoshida

for the COMET Collaboration

大阪大学
OSAKA UNIVERSITY

28th Sep. 2018 @ New Trend in High Energy Physics in Montenegro

Contents

- Introduction
- Overview of COMET experiment
- Status of COMET Phase-I
- Prospects for Phase-II
- Summary

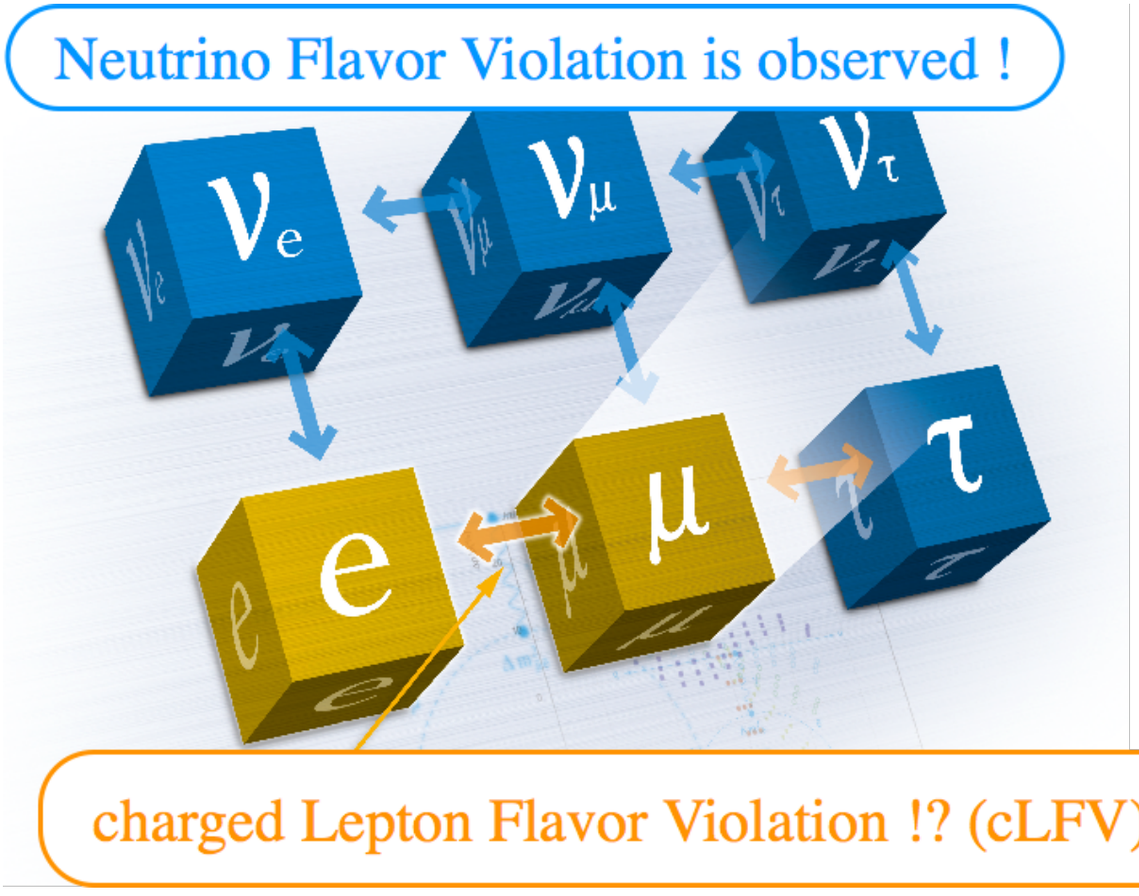
an illustration by higgstan.com

Charged Lepton Flavor Violation

The establishment of the **Standard Model** and the observation of the **Neutrino Oscillation** worked-out very much in the particle physics.

However, There are still mysteries like

- dark matter ?? / dark energy?
- why does our universe consist of dominant “matter” ? (not anti-matter)
- absolute neutrino mass ? why so small ?



Processes of the CLFV

- highly prohibited (O(<10^{-54})) in the SM with Neutrino Oscillation (= no/less SM background)
- are very rare events/decays
- not found yet !
- if found, immediately indicates something beyond the SM

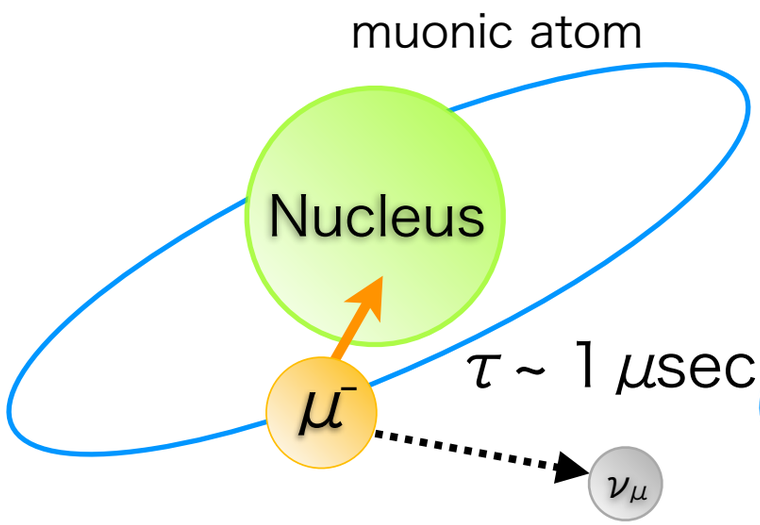
That’s why “CLFV” is interesting!

μ - e conversion search

1. Generate **"muonic atom"** by muon stopping at the target
2. Measure emitted electron momentum from muonic atom
   A. **spectrum of decay in orbit** is Michael edge and longer tail up to 105 MeV
   B. **μ-e conversion signal** is a mono-energetic ~ 105 MeV peak
      (neutrinoless muon decay → emitted electron has all energy of the decay)
3. Spectroscopic search for μ-e conversion signal

Backgrounds in the SM

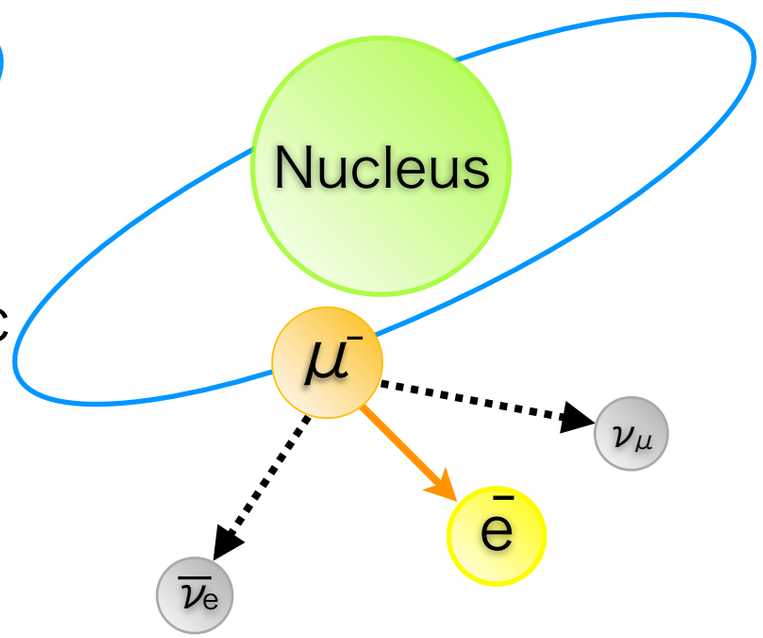
Muon Capture



* electron not emitted

$$\mu^- + N \rightarrow \nu_\mu + N$$

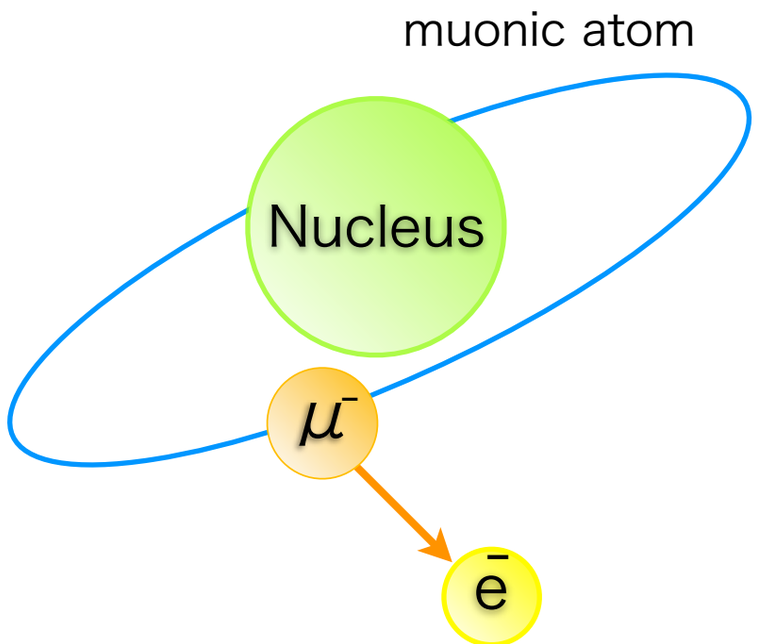
Decay In Orbit (DIO)



$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Signal beyond the SM

μ - e conversion



$$\mu^- N \rightarrow e^- N$$

The COMET Collaboration

200+ collaborators,
40 institutes
from 17 countries

R. Abramishvili[11], G. Adamov[11], R. Akhmetshin[6,31], V. Anishchik[4], M. Aoki[32], Y. Arimoto[18], I. Bagaturia[11], Y. Ban[3], A. Bondar[6,31], Y. Calas[7], S. Canfer[33], Y. Cardenas[7], S. Chen[28], Y. E. Cheung[28], B. Chiladze[35], D. Clarke[33], M. Danilov[15,26], P. D. Dauncey[14], W. Da Silva[23], C. Densham[33], G. Devidze[35], P. Dornan[14], A. Drutskoy[15,26], V. Duginov[16], L. Epshteyn[6,30,31], P. Evtoukhovich[16], G. Fedotovich[6,31], M. Finger[8], M. Finger Jr[8], Y. Fujii[18], Y. Fukao[18], E. Gillies[14], D. Grigoriev[6,30,31], K. Gritsay[16], E. Hamada[18], R. Han[1], K. Hasegawa[18], I. H. Hasim[32], O. Hayashi[32], Z. A. Ibrahim[24], Y. Igarashi[18], F. Ignatov[6,31], M. Iio[18], M. Ikeno[18], K. Ishibashi[22], S. Ishimoto[18], T. Itahashi[32], S. Ito[32], T. Iwami[32], X. S. Jiang[2], P. Jonsson[14], T. Kachelhoffer[7], V. Kalinnikov[16], F. Kapusta[23], H. Katayama[32], K. Kawagoe[22], N. Kazak[5], V. Kazanin[6,31], B. Khazin[6,31], A. Khvedelidze[16,11], T. K. Ki[18], M. Koike[39], G. A. Kozlov[16], B. Krikler[14], A. Kulikov[16], E. Kulish[16], Y. Kuno[32], Y. Kuriyama[21], Y. Kurochkin[5], A. Kurup[14], B. Lagrange[14,21], M. Lancaster[38], M. J. Lee[12], H. B. Li[2], W. G. Li[2], R. P. Litchfield[14,38], T. Loan[29], D. Lomidze[11], I. Lomidze[11], P. Loveridge[33], G. Macharashvili[35], Y. Makida[18], Y. Mao[3], O. Markin[15], Y. Matsumoto[32], A. Melnik[5], T. Mibe[18], S. Mihara[18], F. Mohamad Idris[24], K. A. Mohamed Kamal Azmi[24], A. Moiseenko[16], Y. Mori[21], M. Moritsu[32], E. Motuk[38], Y. Nakai[22], T. Nakamoto[18], Y. Nakazawa[32], J. Nash[14], J. -Y. Nief[7], M. Nioradze[35], H. Nishiguchi[18], T. Numao[36], J. O'Dell[33], T. Ogitsu[18], K. Oishi[22], K. Okamoto[32], C. Omori[18], T. Ota[34], J. Pasternak[14], C. Plostinar[33], V. Ponariadov[45], A. Popov[6,31], V. Rusinov[15,26], B. Sabirov[16], N. Saito[18], H. Sakamoto[32], P. Sarin[13], K. Sasaki[18], A. Sato[32], J. Sato[34], Y. K. Semertzidis[12,17], N. Shigyo[22], D. Shoukavy[5], M. Slunecka[8], A. Straessner[37], D. Stöckinger[37], M. Sugano[18], Y. Takubo[18], M. Tanaka[18], S. Tanaka[22], C. V. Tao[29], E. Tarkovsky[15,26], Y. Tevzadze[35], T. Thanh[29], N. D. Thong[32], J. Tojo[22], M. Tomasek[10], M. Tomizawa[18], N. H. Tran[32], H. Trang[29], I. Trekov[35], N. M. Truong[32], Z. Tsamalaidze[16,11], N. Tsverava[16,35], T. Uchida[18], Y. Uchida[14], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[10], W. A. T. Wan Abdullah[24], M. Warren[38], M. Wing[38], M. L. Wong[32], T. S. Wong[32], C. Wu[2,28], H. Yamaguchi[22], A. Yamamoto[18], T. Yamane[32], Y. Yang[22], W. Yao[2], B. K. Yeo[12], H. Yoshida[32], M. Yoshida[18], Y. Yoshii[18], T. Yoshioka[22], Y. Yuan[2], Yu. Yudin[6,31], J. Zhang[2], Y. Zhang[2], K. Zuber[37]

+ more

COMET Experiment

Search for "μ-e conversion" in Japan at J-PARC hadron hall

Experimental Target : $B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$ (S.E.S)

This is **10,000 times improvement**
from the current limit given by the SINDRUM II experiment (2006).

Current World Limit : $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$

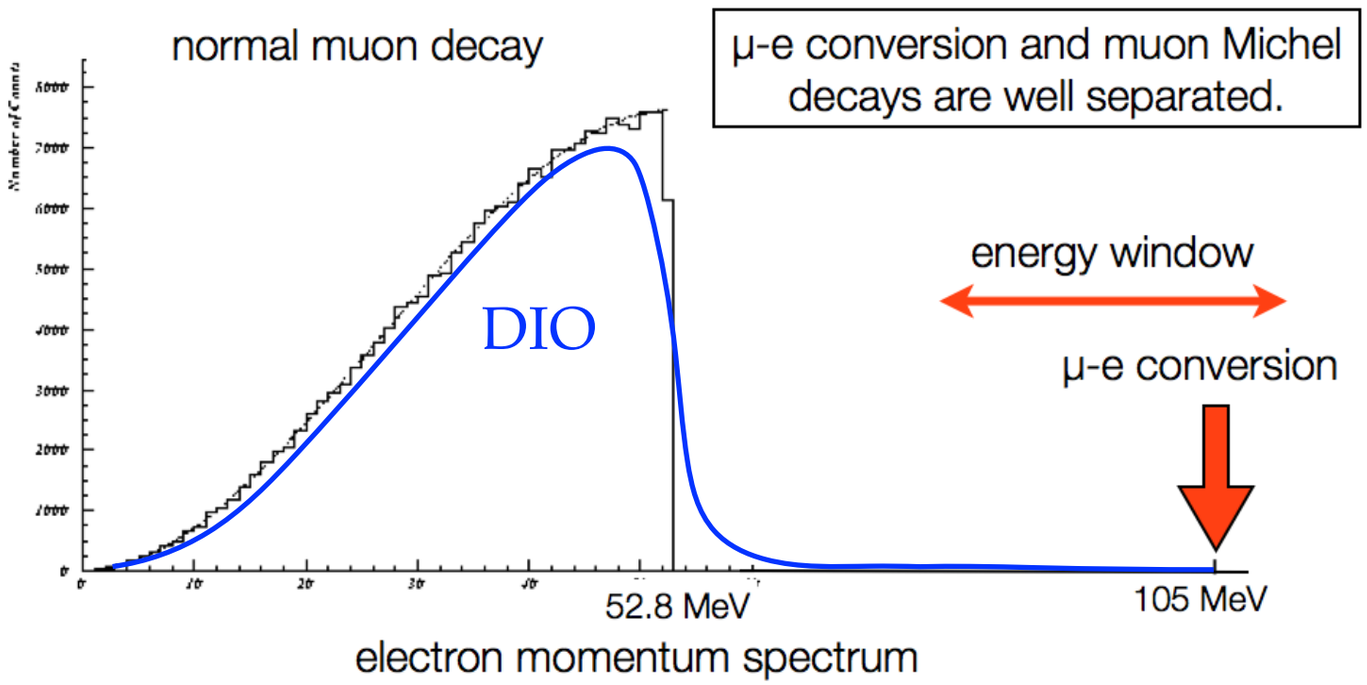
Important Keys for COMET

1. Increase of Muon Intensity with an Innovative Pion Capture System

   MuSIC in RCNP-Osaka University demonstrated more than x 10^3 improvement of pion capture efficiency with larger target and surrounding superconducting solenoid to capture pions.

2. Reduction of Background by Detector System and Pulsed-Beam

Backgrounds Reduction



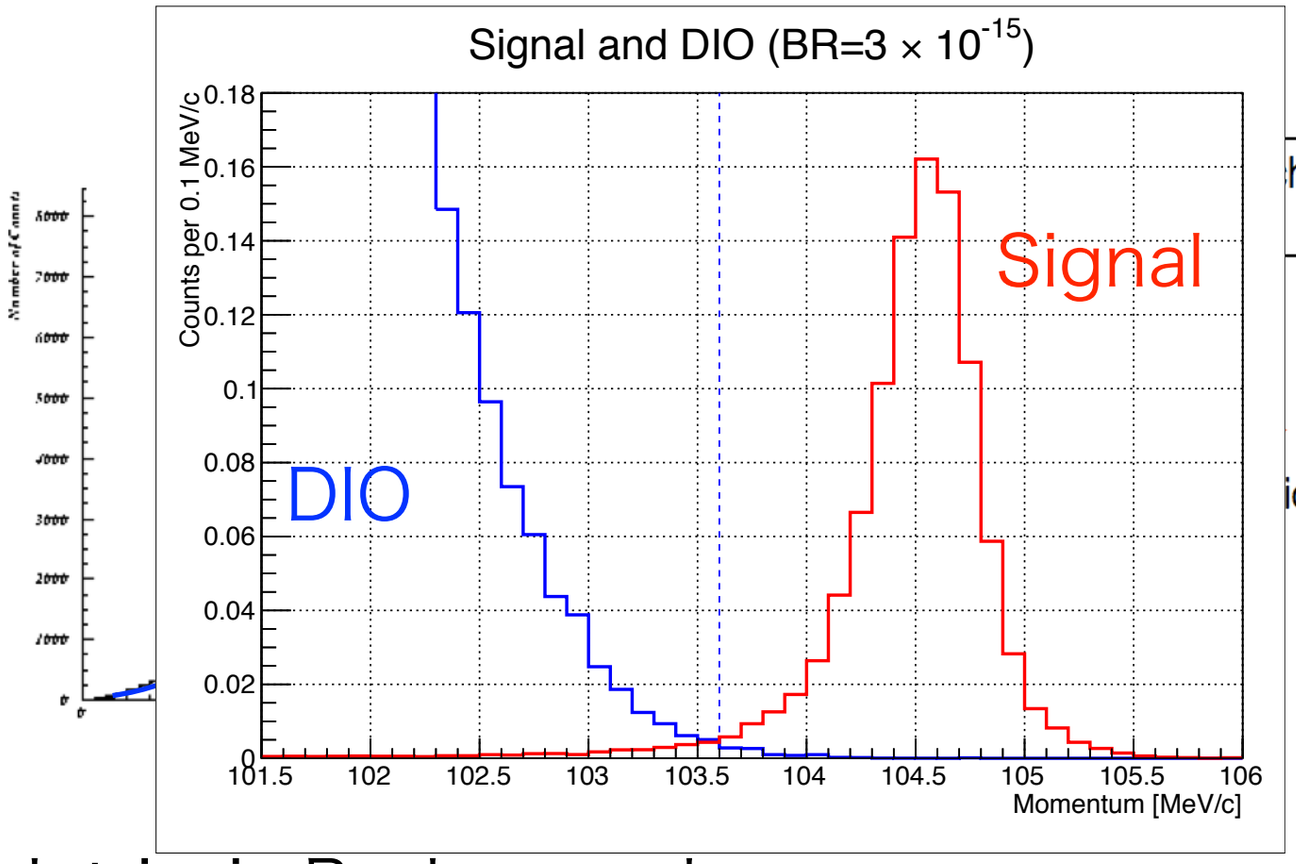
Intrinsic Background

DIO spectrum has longer tail up to ~105 MeV

→ require **high momentum resolution** of the detector to separate the DIO tail and signal

(extinction factor = # of proton after bunch / # of proton in 1 bunch)

Backgrounds Reduction



Intrinsic Background

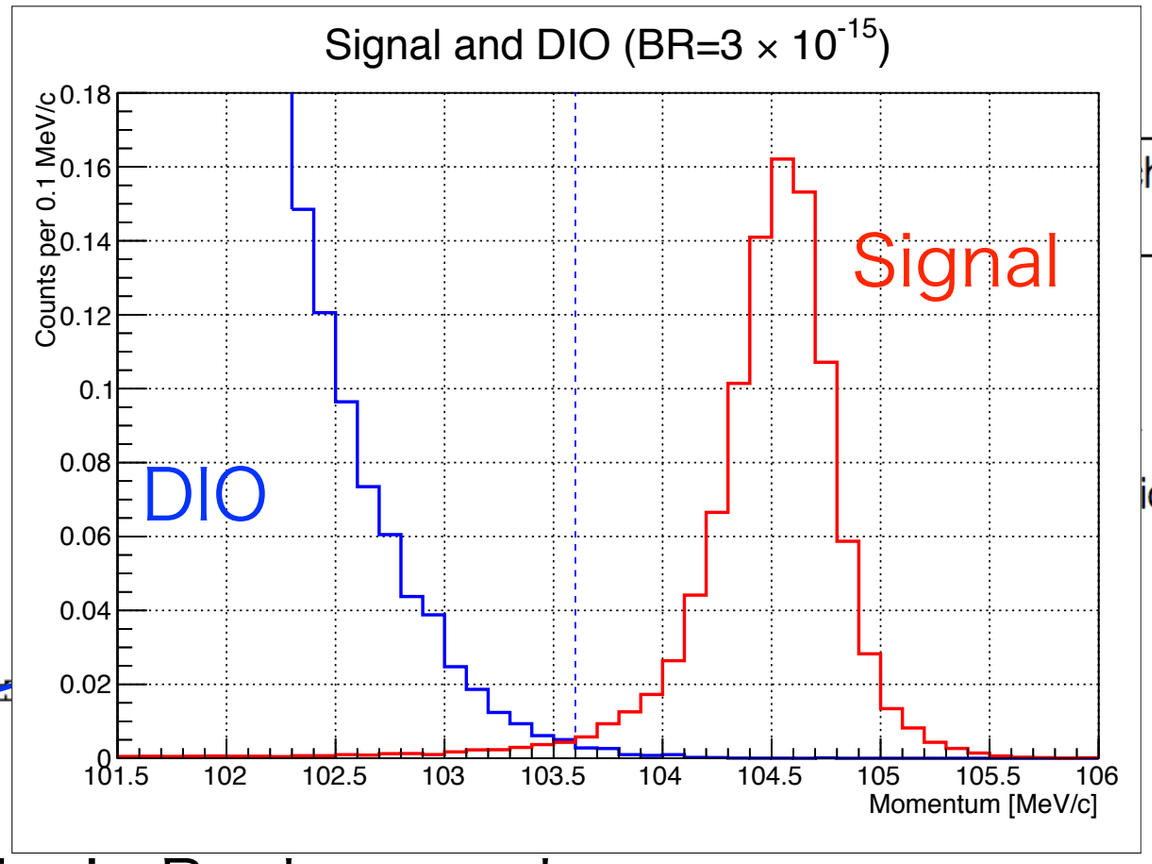
DIO spectrum has longer tail up to ~105 MeV

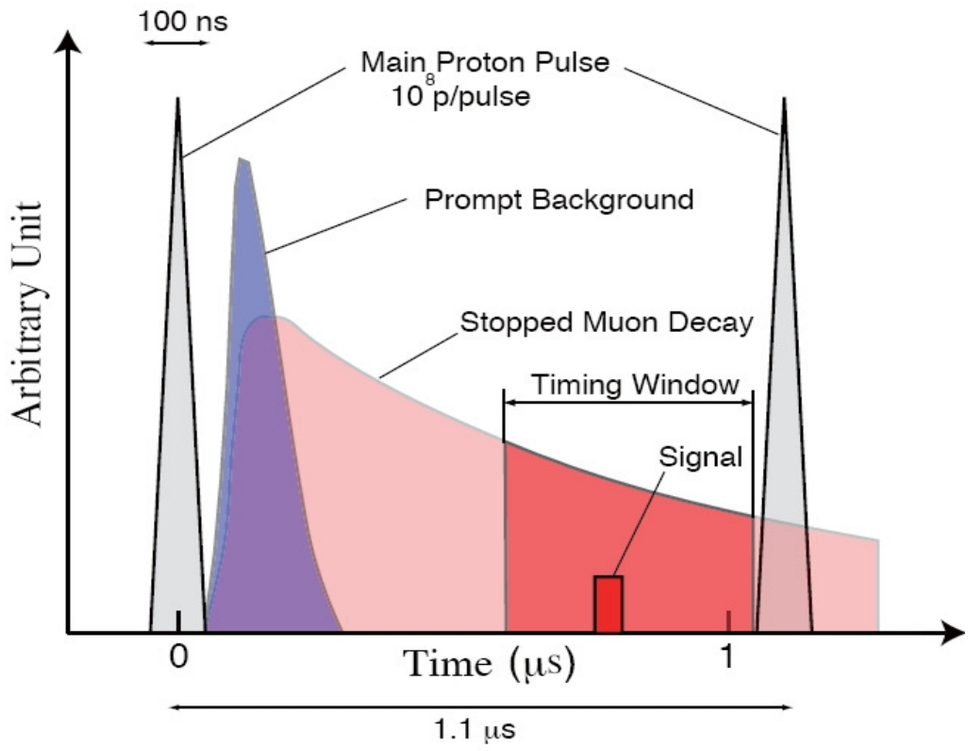
→ require **high momentum resolution** of the detector

to separate the DIO tail and signal

(extinction factor = # of proton after bunch / # of proton in 1 bunch)

Backgrounds Reduction





Intrinsic Background

DIO spectrum has longer tail up to ~105 MeV

→ require **high momentum resolution** of the detector

to separate the DIO tail and signal

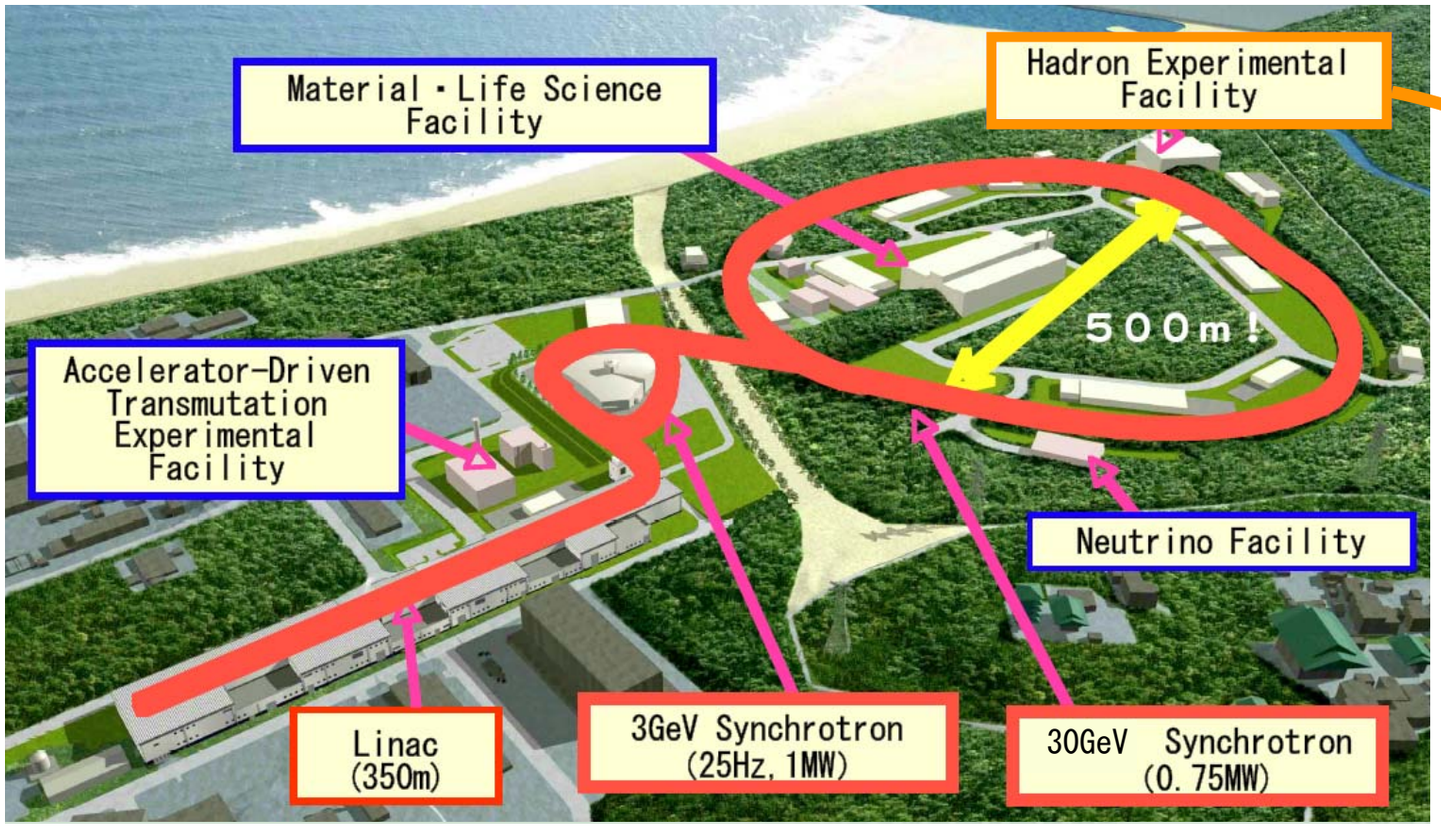
Beam-related Background

Radiative pion capture, muon decay in flight and so on

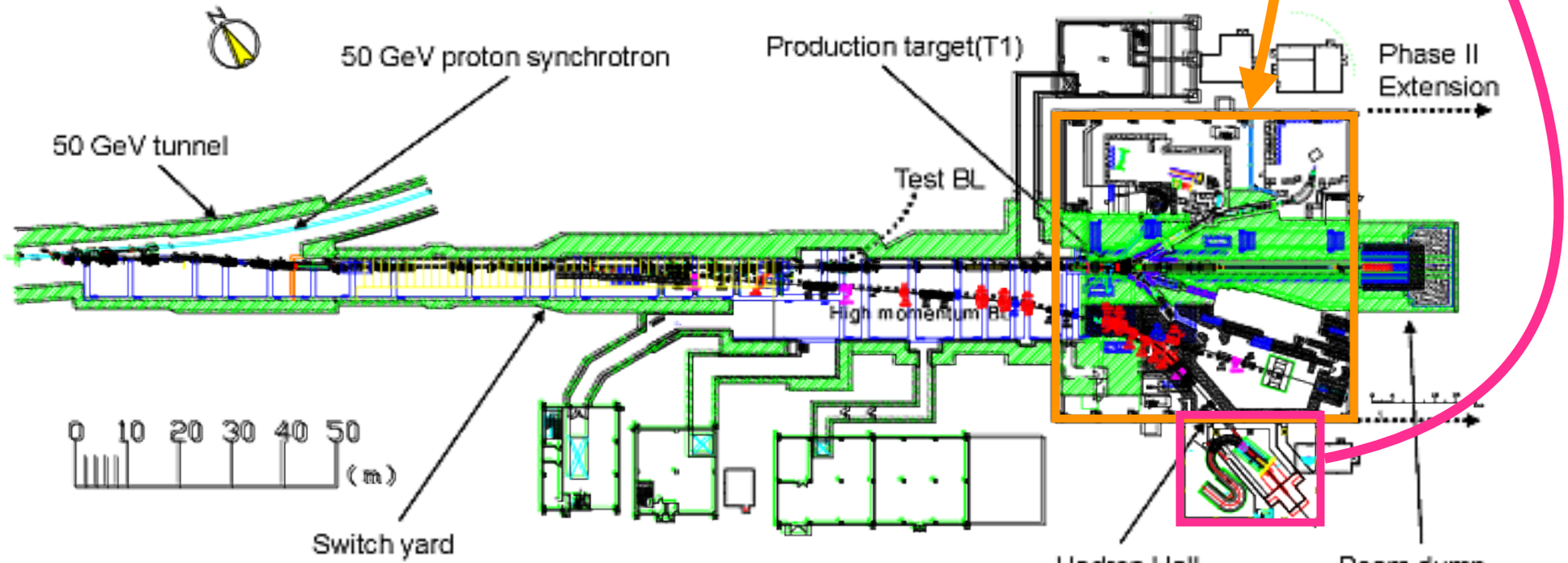
→ require **pulsed beam** and **excellent proton extinction < 10^{-10}**

(extinction factor = # of proton after bunch / # of proton in 1 bunch)

COMET at J-PARC E21



built in 2015

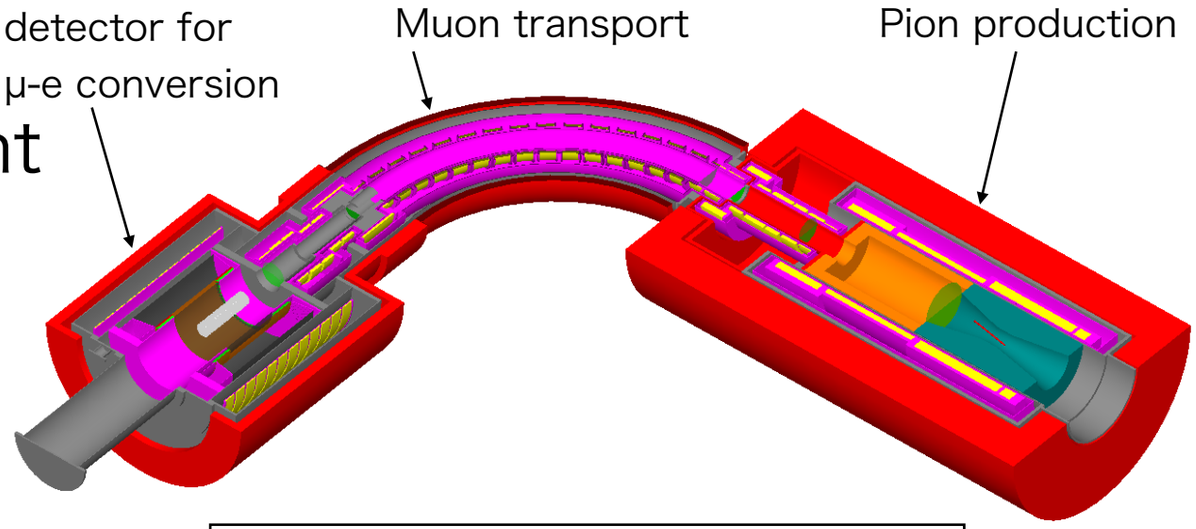


COMET Phase-I

COMET Phase-I Goal :

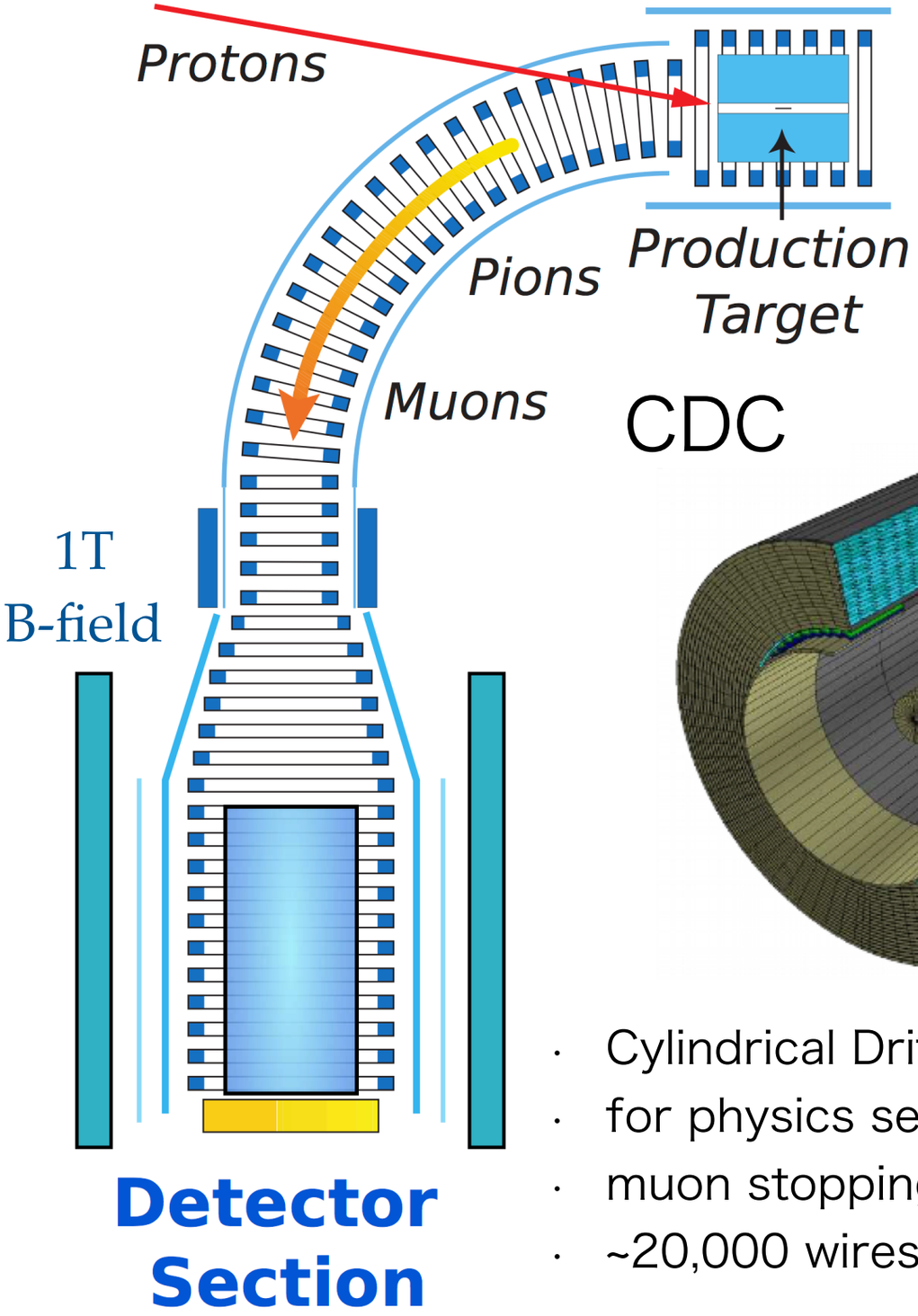
$$B(\mu^- + Al \rightarrow e^- + Al) = 3.0 \times 10^{-15} \quad \text{(S.E.S)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \quad (90\%C.L.)$$

- With shorter muon transport solenoid (90° bending)
- Not-full power operation of proton beam (3.2 kW)
- **Quick and Low-Cost Construction** to get result earlier
  - under construction since ~2013, budget funded (almost fully).
  - will be completed the detector construction in 2019
- Containing R&D for Phase-II
  - Background Measurement
  - Detector Study and Development
- COMET Project is approved by J-PARC in summer 2016
- Technical Design Report is being updated as 2018 version.



COMET Phase-I Layout

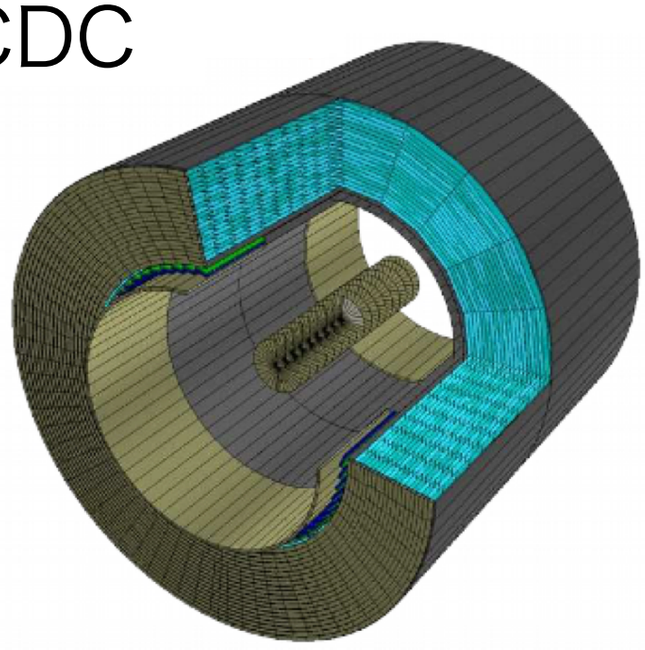
COMET Phase-I Detectors



Pion Capture Section

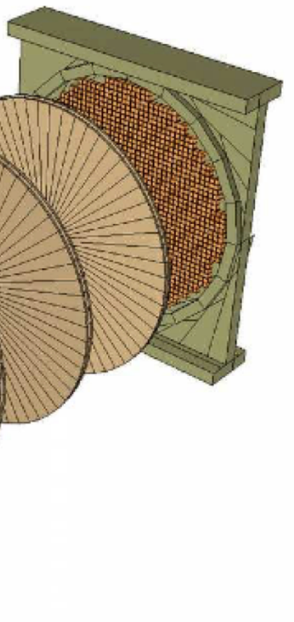
Detector Section

CDC



- Cylindrical Drift Chamber
- for physics search in Phase-I
- muon stopping target at center
- ~20,000 wires with He base gas

StrawECAL

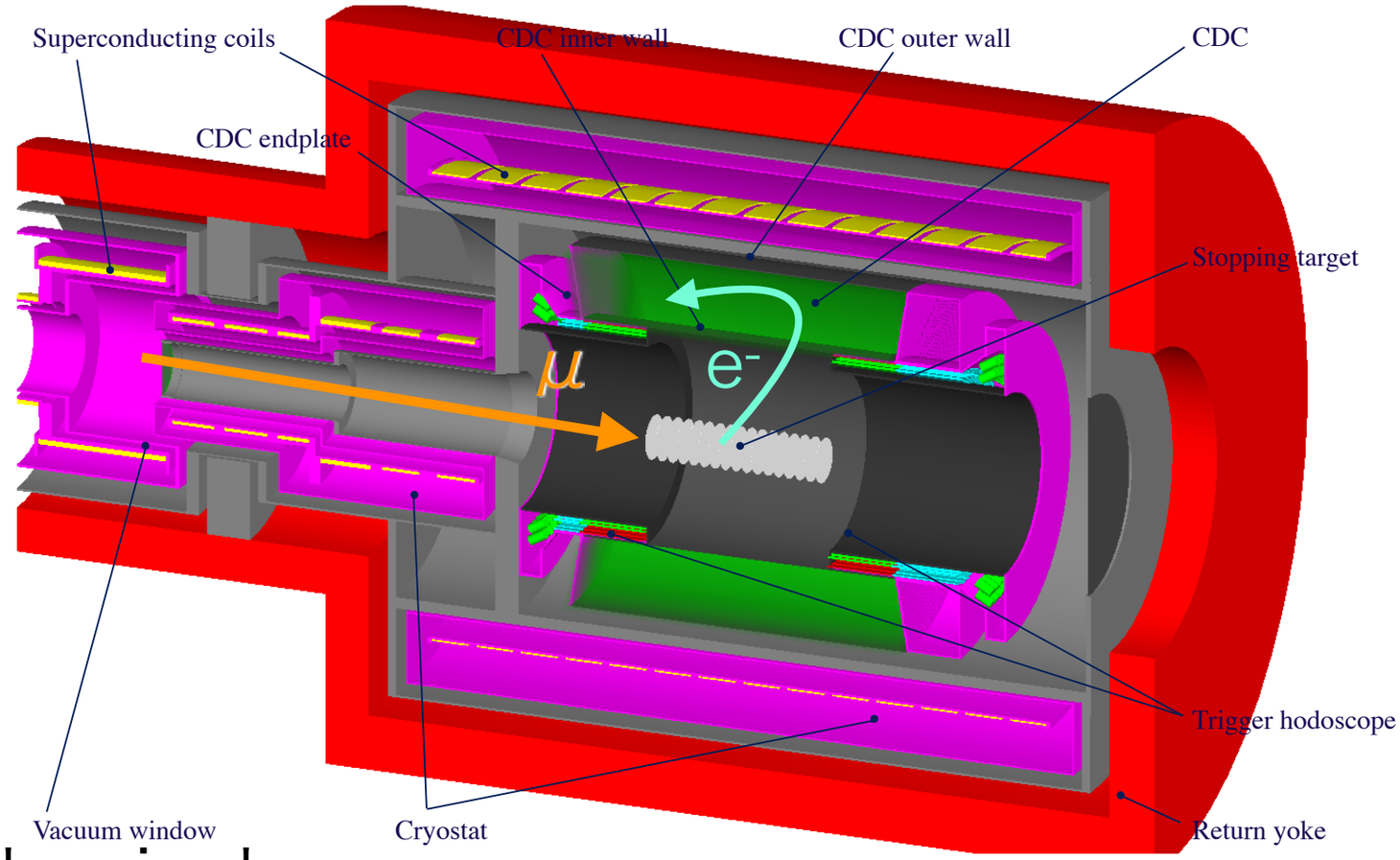


- Straw Tracker
  + Electron Calorimeter
- for beam background measurement
- also as R&D for Phase-II

Cylindrical Drift Chamber

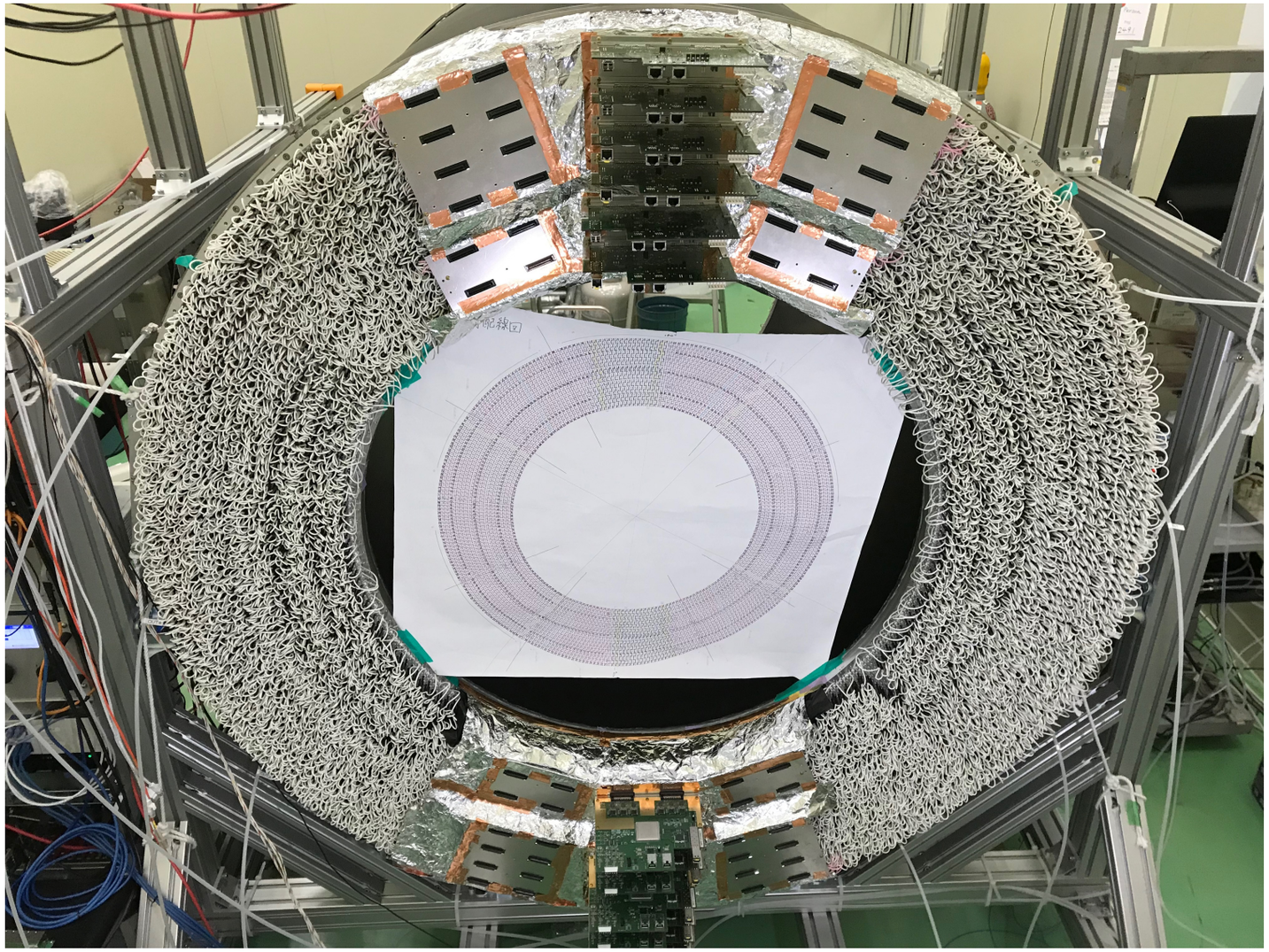
COMET CDC

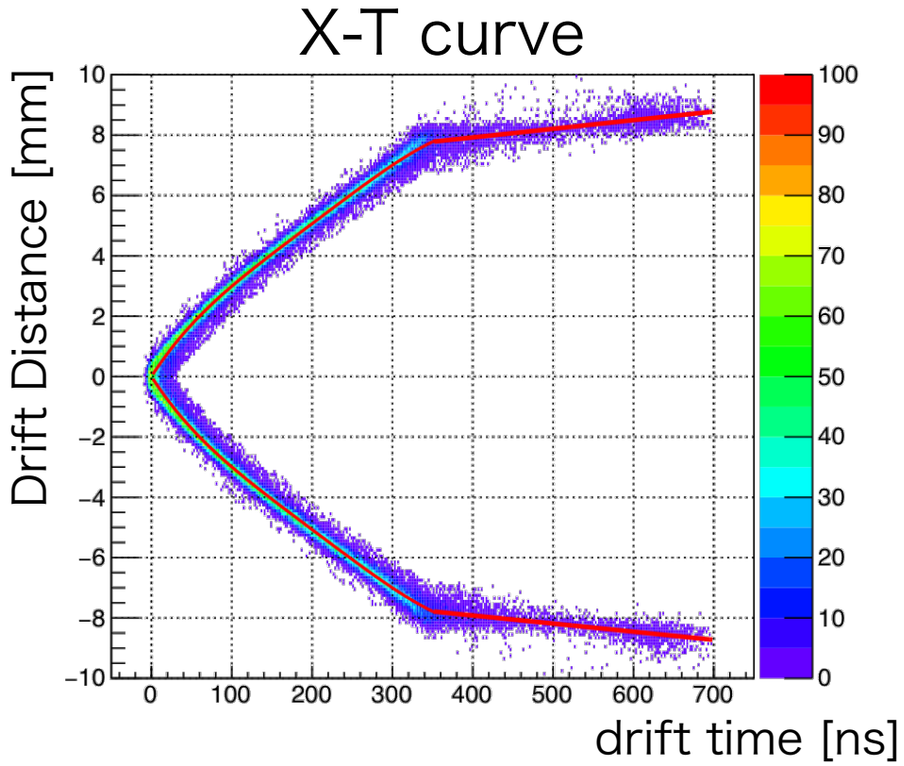
- Surrounding target
- 19 layers structure
  ~5,000 sense wires
  ~15,000 field wires
- All stereo layers
- He base gas
  (He : iC_4H_{10} = 90 : 10)

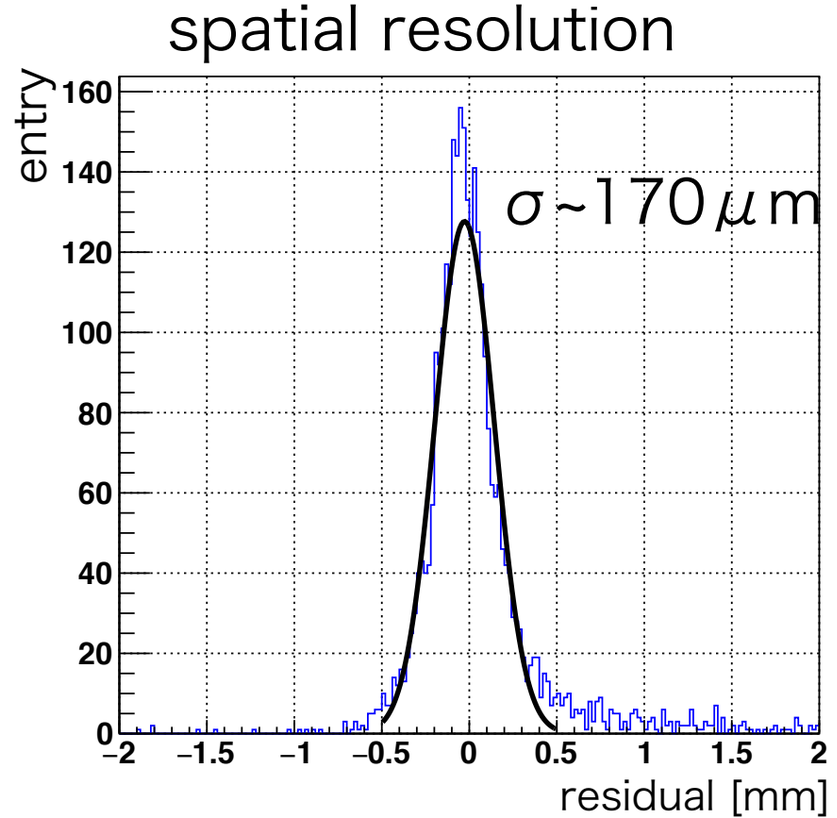


- Study of prototype chamber is done
  - basic performance study was done, it is OK
  - spatial resolution < 200 μm obtained
  - wire aging test is almost done
- Design was fixed based on Belle-II CDC with modification for COMET
- Construction started in 2014, and completed in 2016
- Commissioning with cosmic-ray is ongoing in KEK now

COMET CDC Commissioning

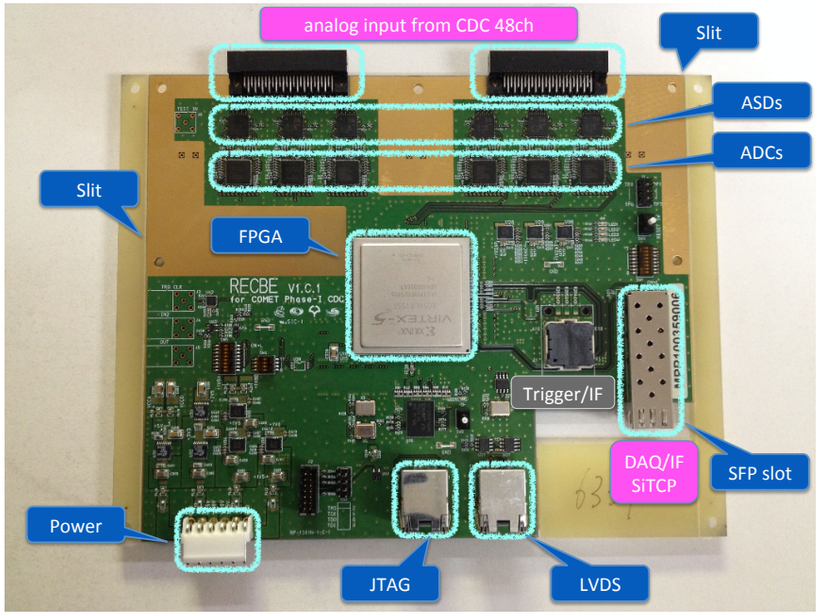






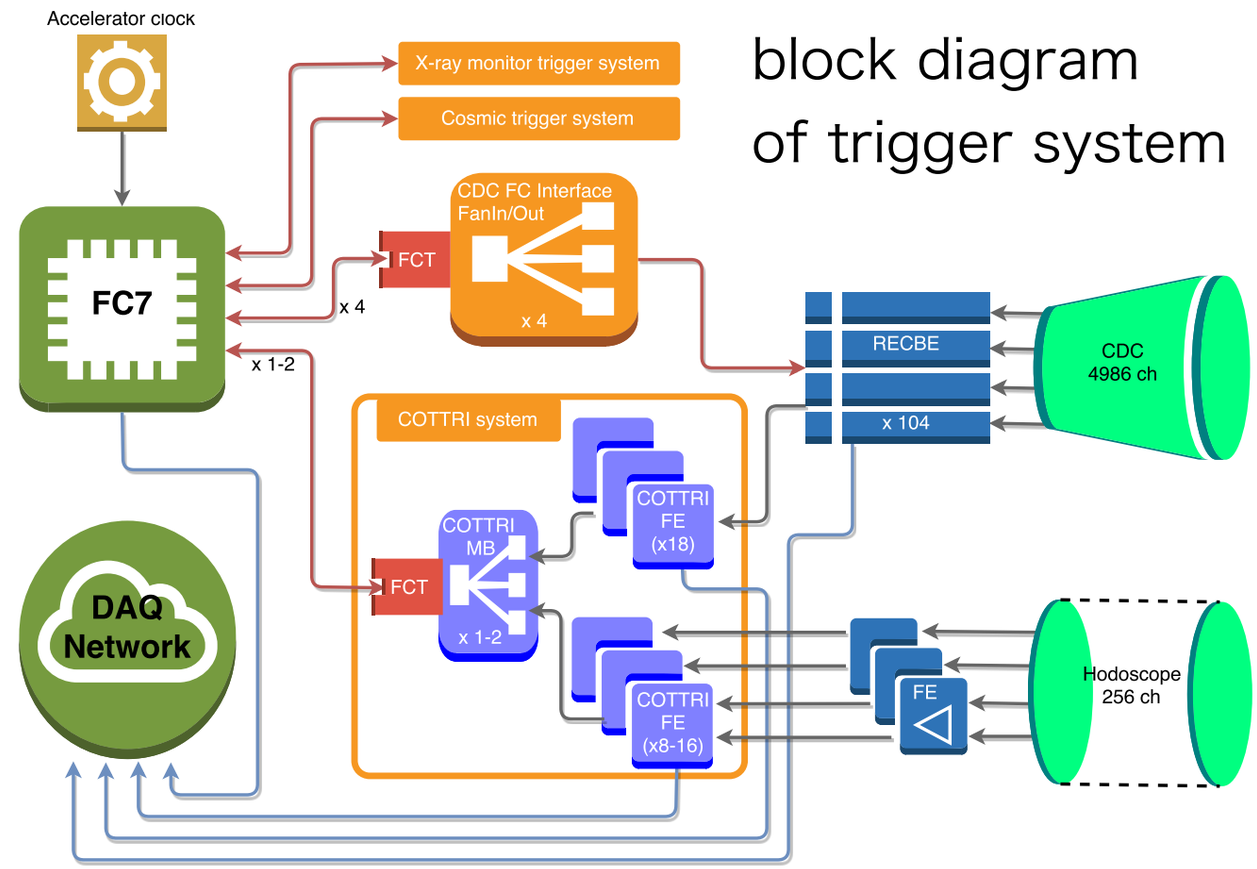
- Cosmic-ray test is ongoing in KEK Fuji B4
- Basic performance test is evaluated.
  → Good performance was obtained so far.
- Trying to increase active channels.
- Development of related sub-system is ongoing.

Read-out Electronics and DAQ

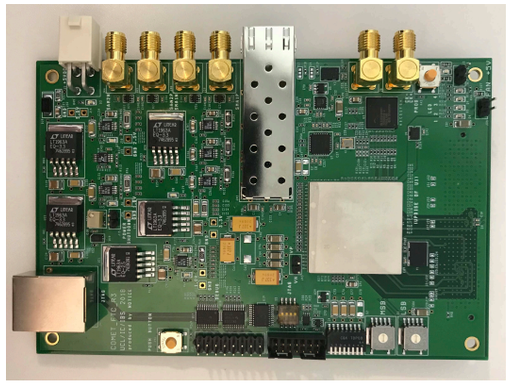


RECBE (semi-copy of Belle-II CDC read-out)

- 48ch read-out per board
- 960MHz TDC and 10bit ADC
- 1Gbps SiTCP communication
- 128 RECBEs mass production done!
- firmware development ongoing

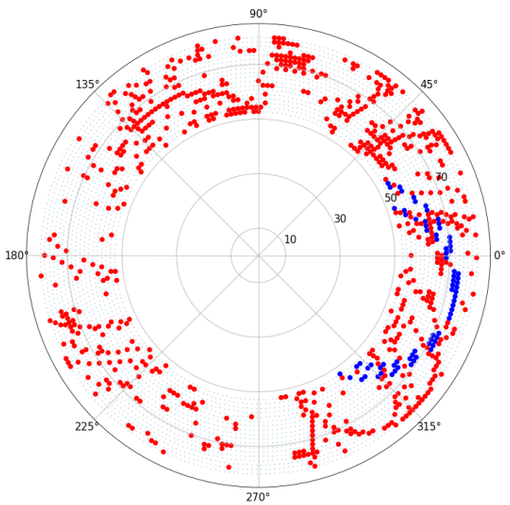


block diagram
of trigger system



FCT board

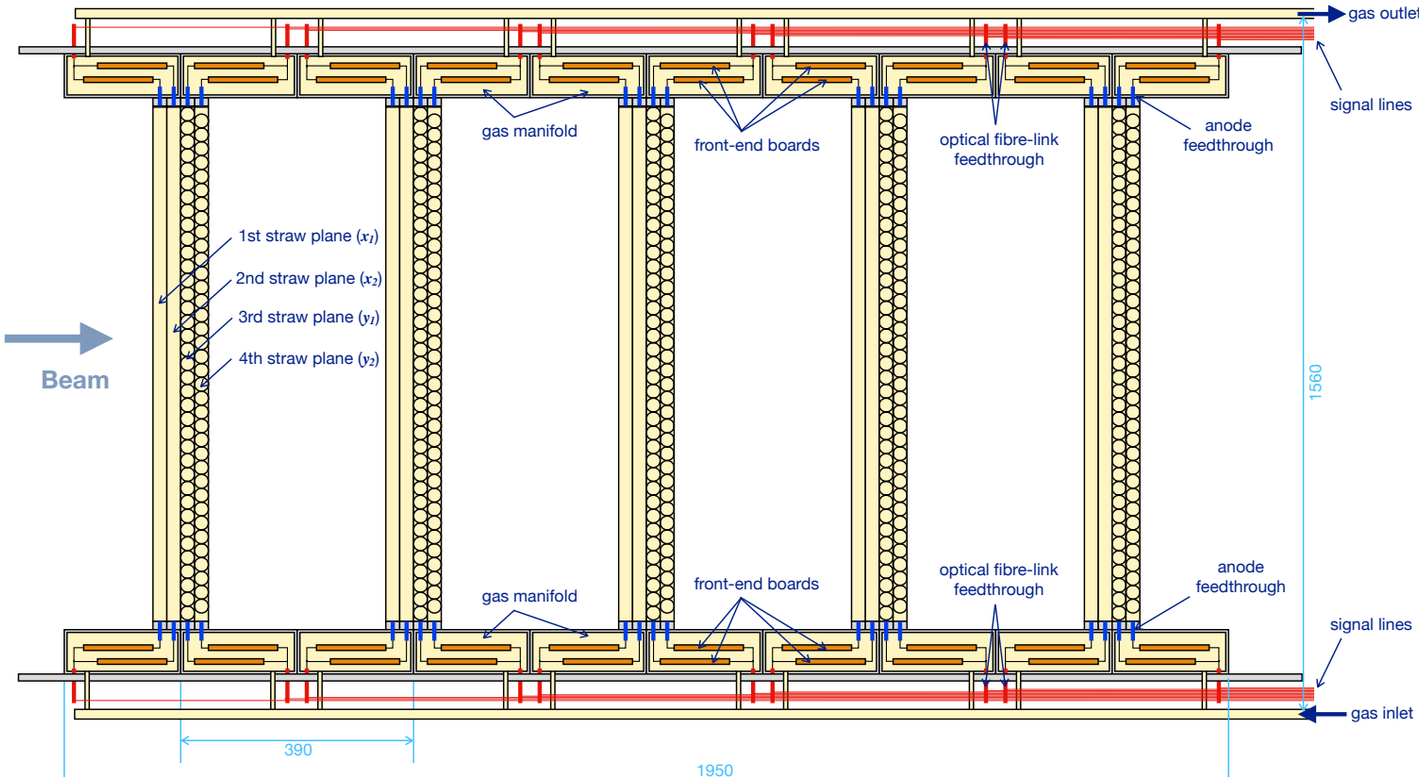
- intermediate board between trigger and various read-out
- prototyping done



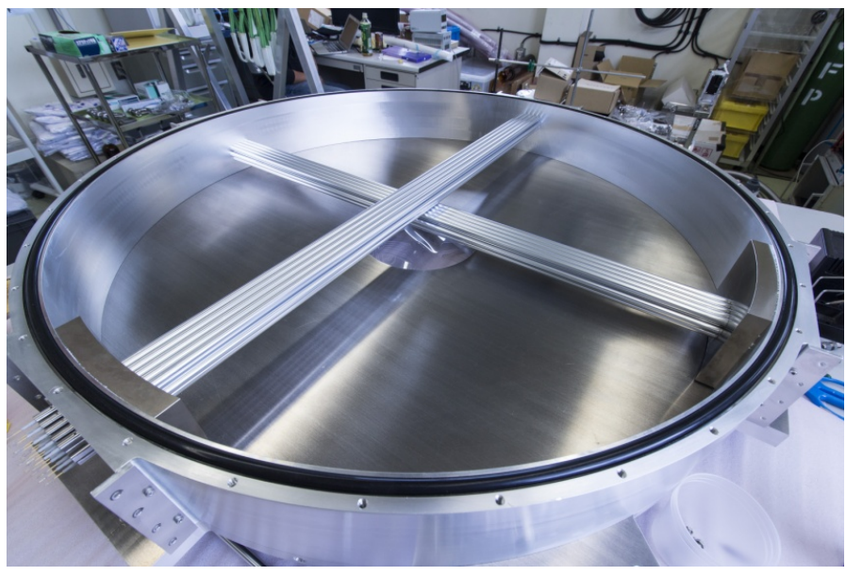
Tracking Trigger

- triggering with track finding to reduce trigger rate
- under development

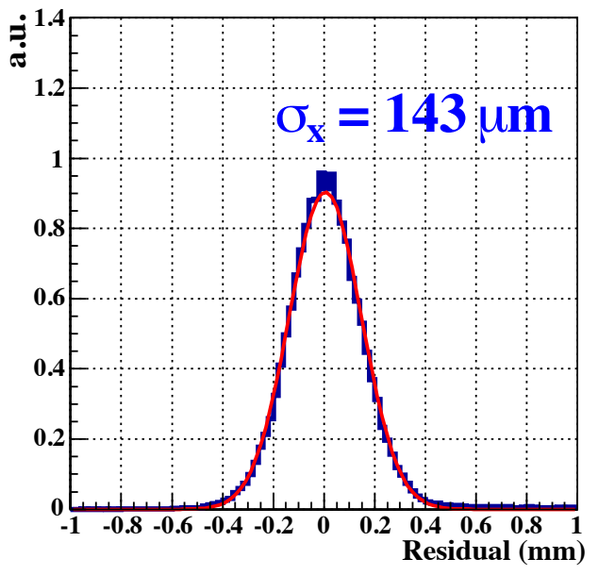
Strawtube Tracker



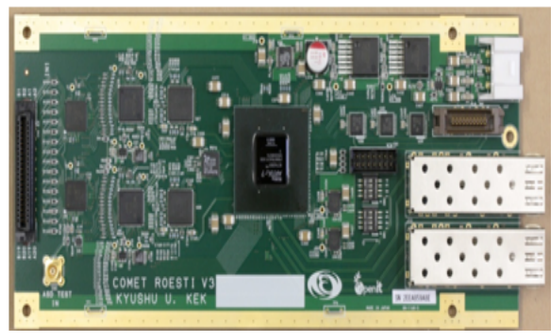
- Tracker of Straw-tubes
  - 9.75mm diameter
  - 20 μm thickness
  - 2-Dimensional config.
  - a station has 2x2 layers
  - 5 stations for Phase-I
- Δp = 150~200 keV/c (for 105 MeV/c electron)
- Ar:C_2H_6=50:50



Prototype Straw Station

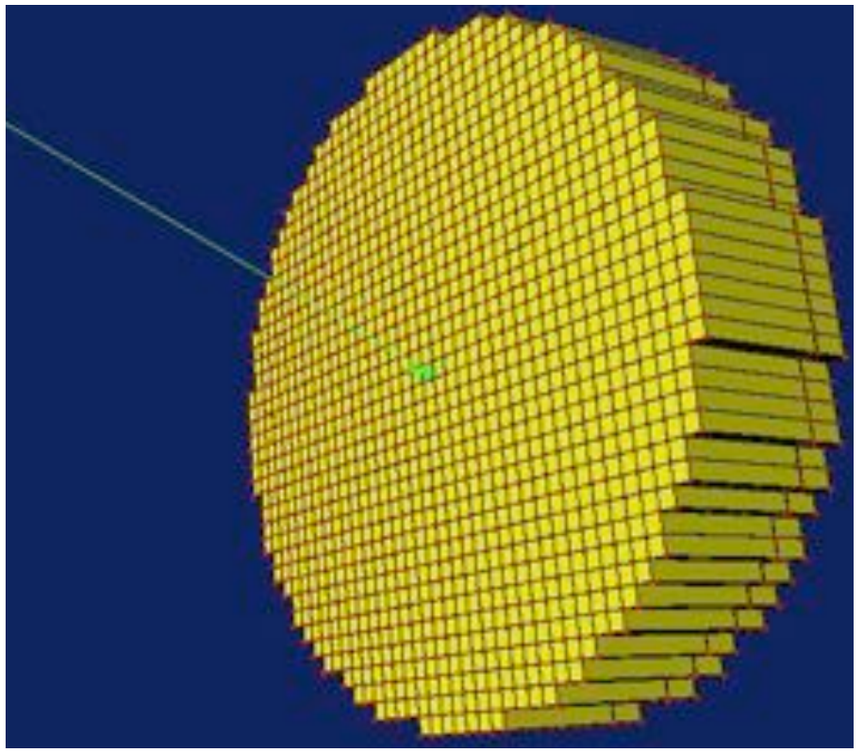


Spatial Resolution

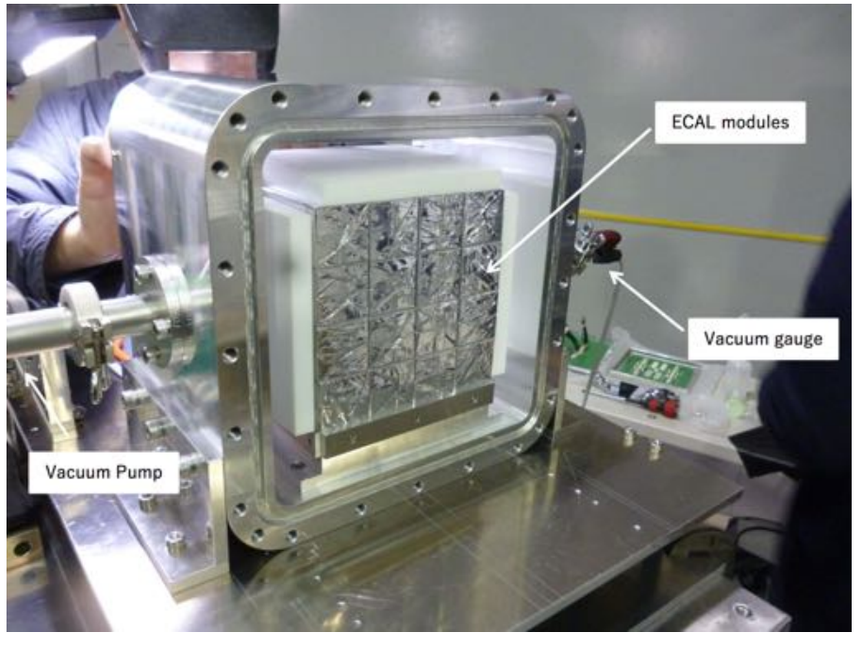


ROESTI : read-out electronics (developed for COMET, DRS4)

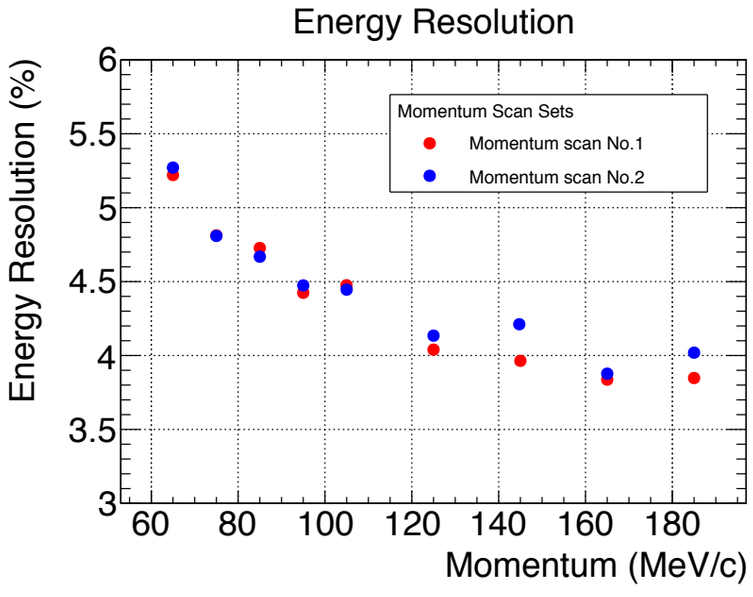
Electron Calorimeter (ECAL)

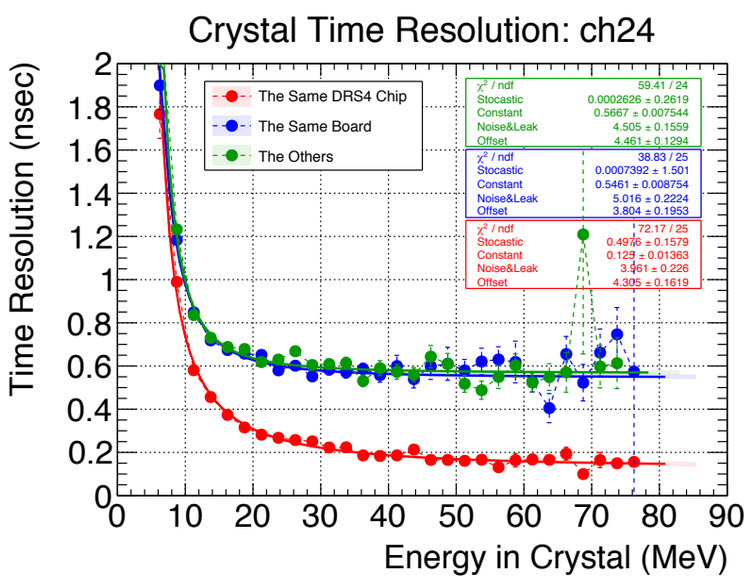


- Energy Measurement for PID
  - at end-cap of the detector system
  - combination of 1920 LYSO crystals
  - 2x2x12 cm (10.5 radiation length)
- Making trigger decision
- Event timing measurement
- ⊿E/E = 5% (for E = 105 MeV)
- APD + read-out (EROS)



prototype of ECAL system

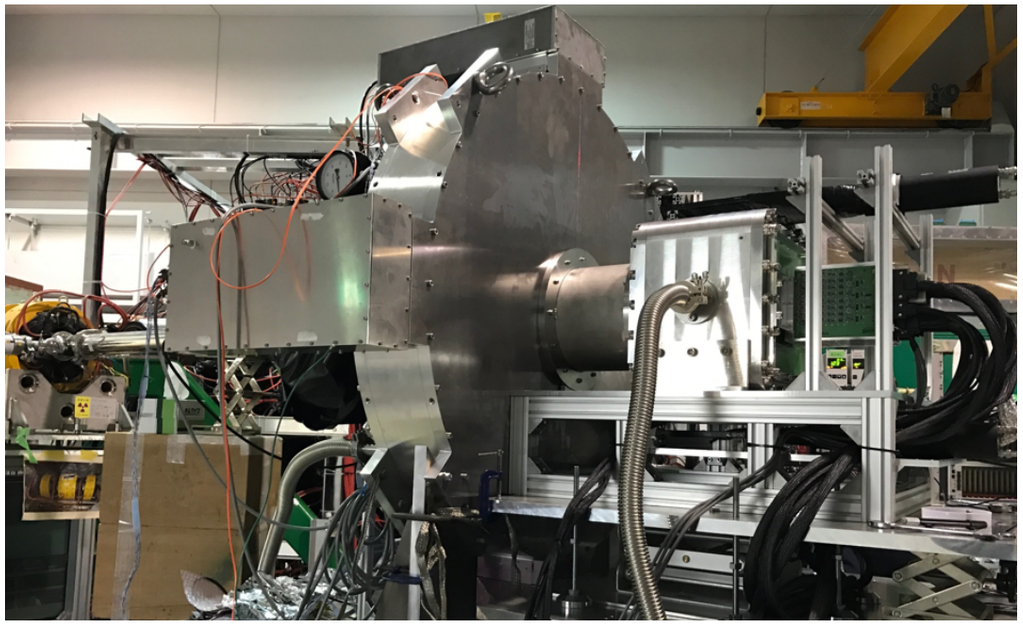




performance test results

StrECAL system

Integration tests of StrECAL system were performed at ELPH in Tohoku Univ.



- with prototype of Strawtube Tracker and prototype of ECAL
- operation in **vacuum** same as real system
- 100 MeV/c electron beam
- successfully triggered by the ECAL and the electron track was reconstructed with the Strawtube Tracker.
- The prototype of trigger system was tested.

Current Status

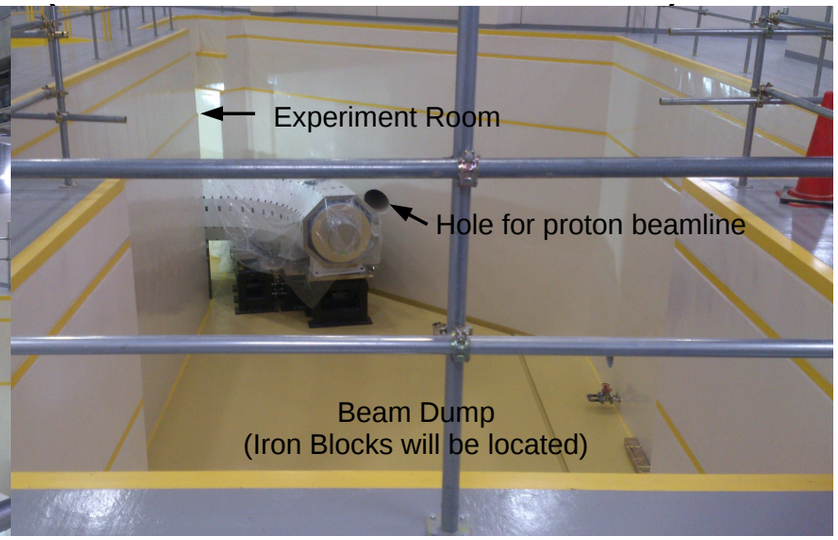
- Strawtube Tracker
  - the strawtubes were already mass-produced and checked.
  - the 1st station of the real detector will be constructed soon (in the winter)
- ECAL
  - in the process to purchase ~500 LYSO crystal for Phase-I
  - the design work for the real detector is also ongoing

Construction of Hall and Beam-line

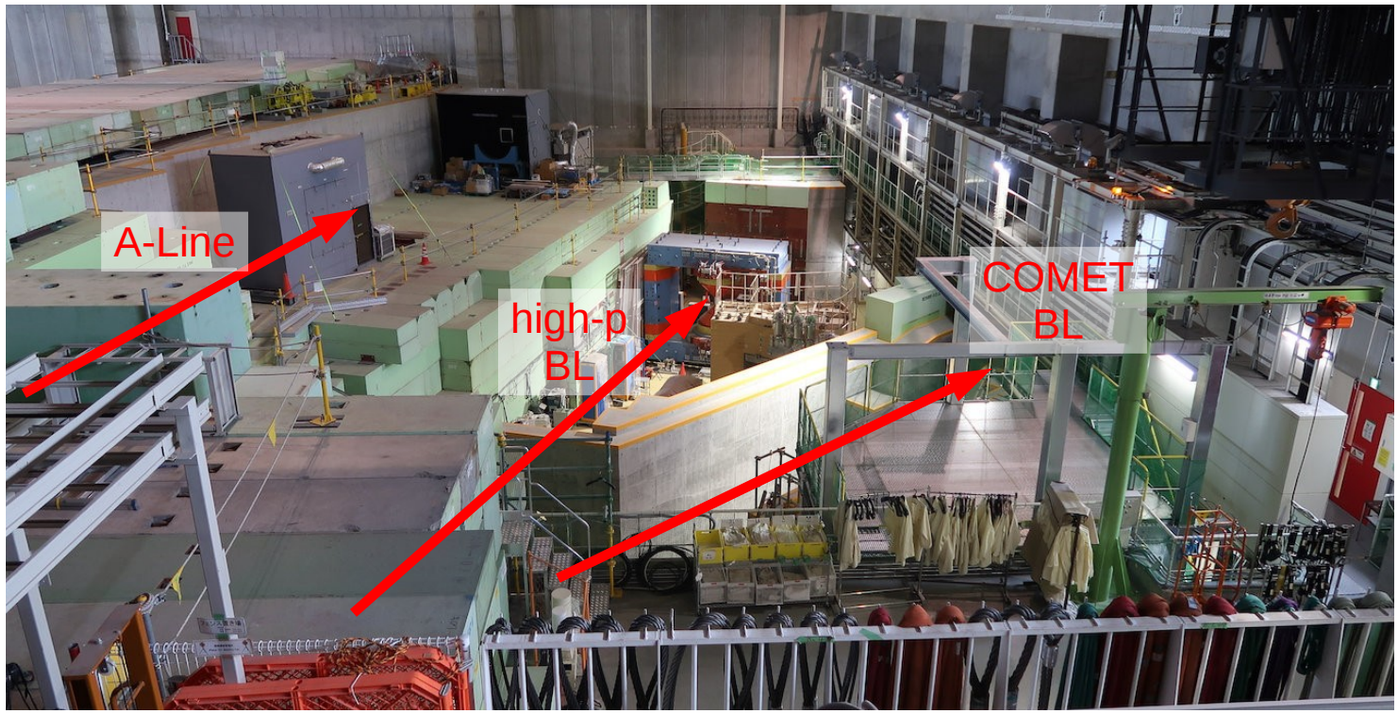
COMET Hall next to Hadron Hall

Installation Yard

Experimental Room



COMET Beam-line Wall in Hadron Hall was built

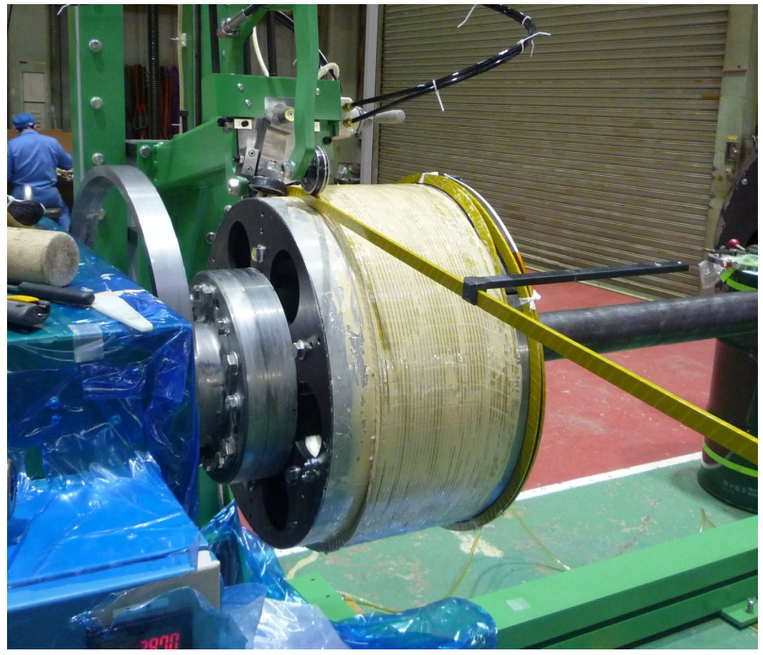


Construction of Solenoid

Pion capture solenoid system

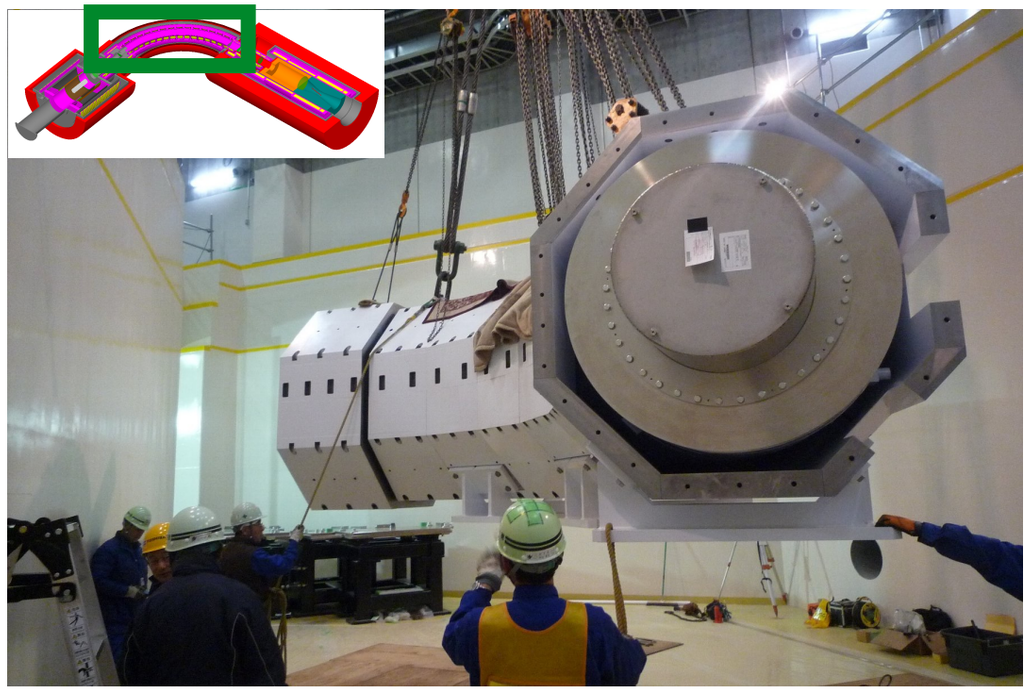
- The delivery of aluminum stabilized superconductors is being made (10 km in 2013, 12 km in 2014, and 8 km in 2015).
- TS1a coil winding is made by a new winding machine.
- CS and MS coils were made in 2016

TS1a coil winding



Muon transport solenoid system

- The muon transport system (TS2-TS3) has been constructed and delivered by Toshiba Co. in 2015



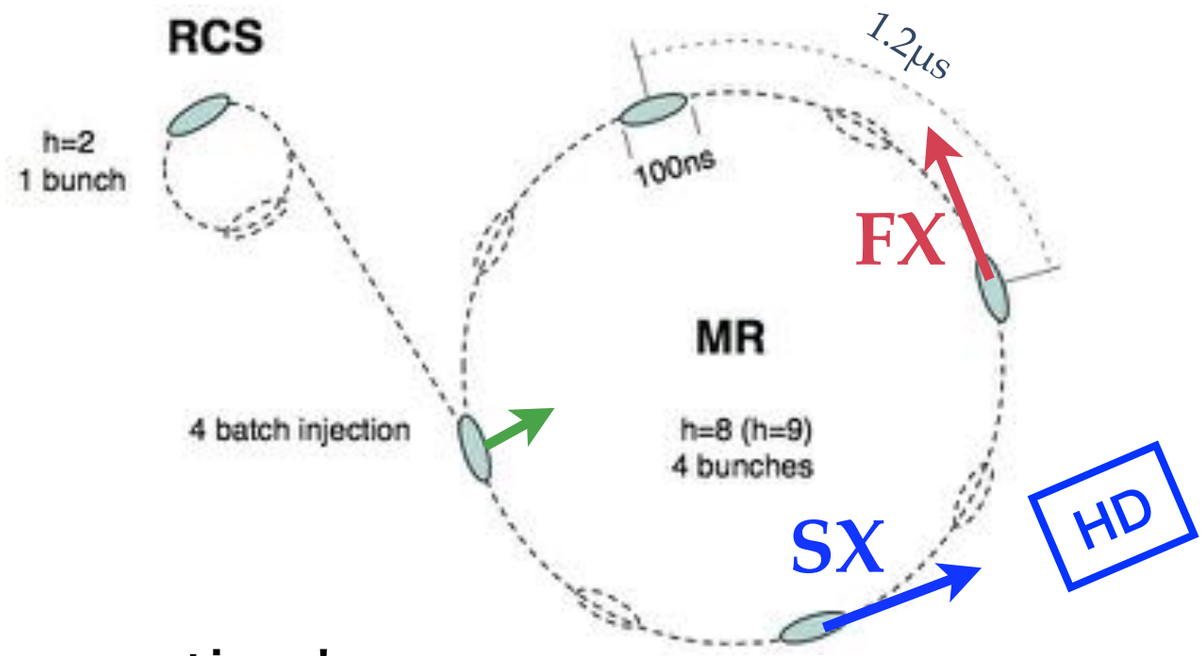
Detector solenoid system

- under construction, will be completed in 2019

8 GeV test and Extinction Measurement

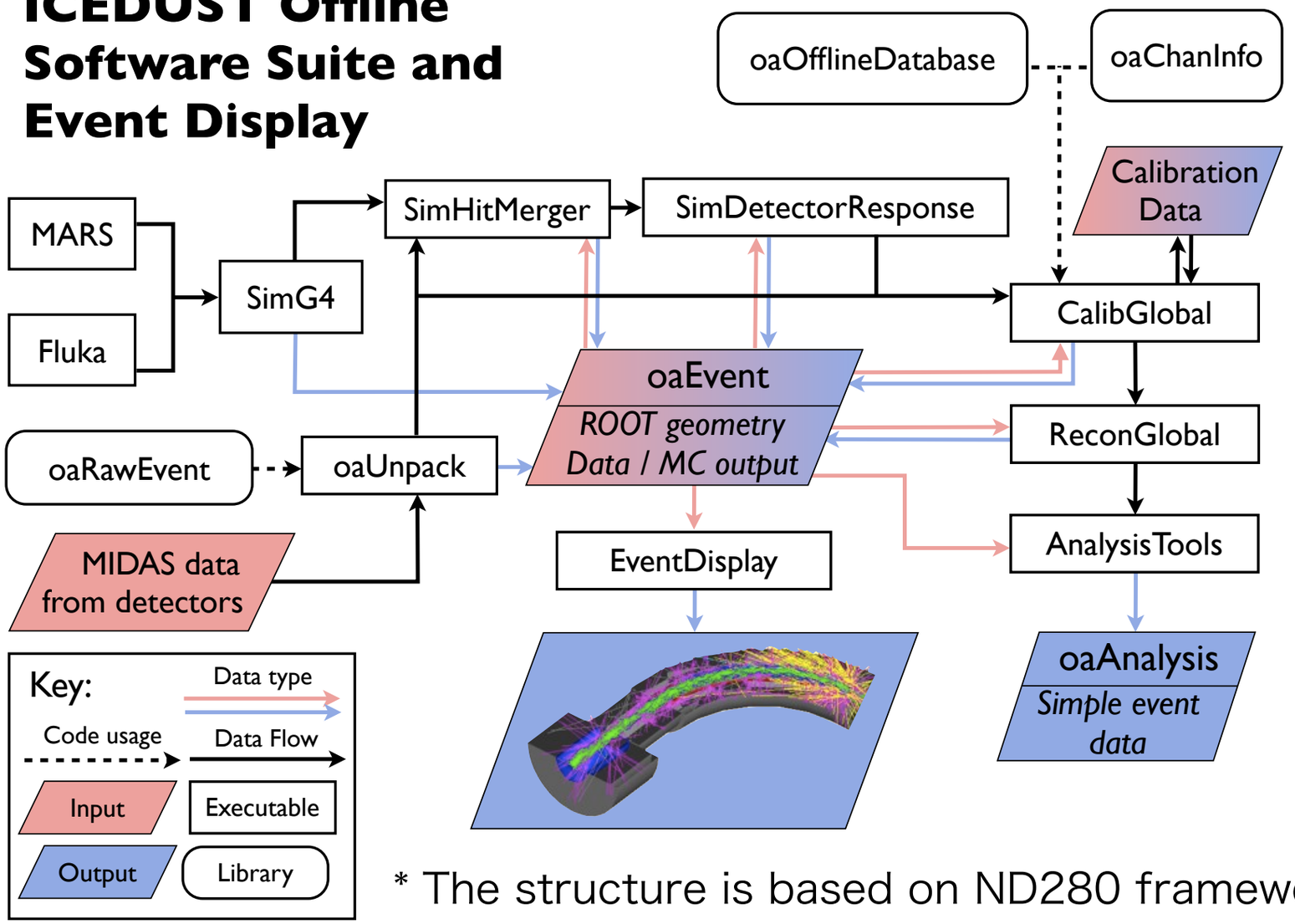
The test was done at J-PARC MR and the measurement was performed at K1.8 beam line at Hadron Hall in Jan. - Feb. 2018.

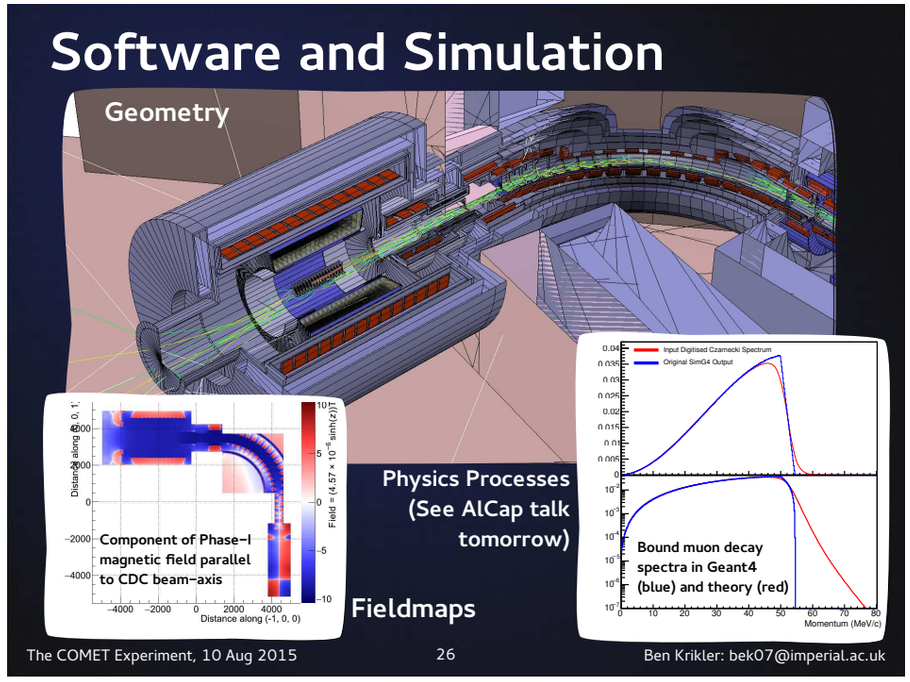
	Normal	COMET
Energy	30 GeV	8 GeV
Extraction	Fast (T2K) Slow (Had.)	Bunched-SX 1b on RCS



- successfully demonstrated the operation!
- extinction was measured by FX&SX both
  - **the 1st demonstration** of COMET mode (8 GeV Bunched-SX)
  - good extinction was < 1.0 x 10^{-10} obtained.
    → the improvement is expected by solving the current issue and increasing the statistics (longer beam time)

Software Framework “ICEDUST”





an example for Phase-I

* The structure is based on ND280 framework.

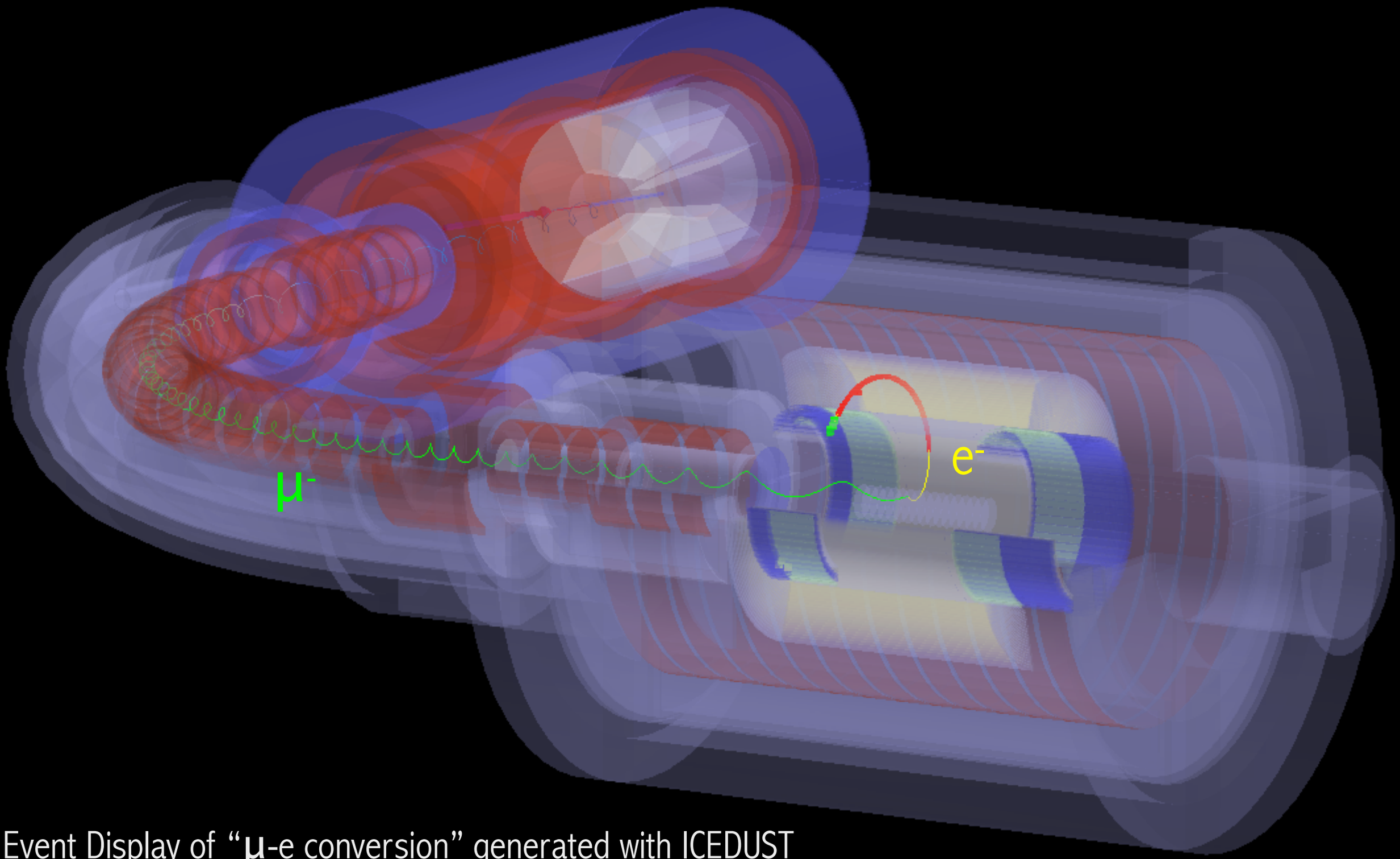
The framework “ICEDUST” has almost been ready in 2015.

Still need to be implemented more, such as detector response.

The simulation and analysis is/will be studied with ICEDUST now.

Mass MC events generation is ongoing for more higher statistics study.

Event Display with ICEDUST

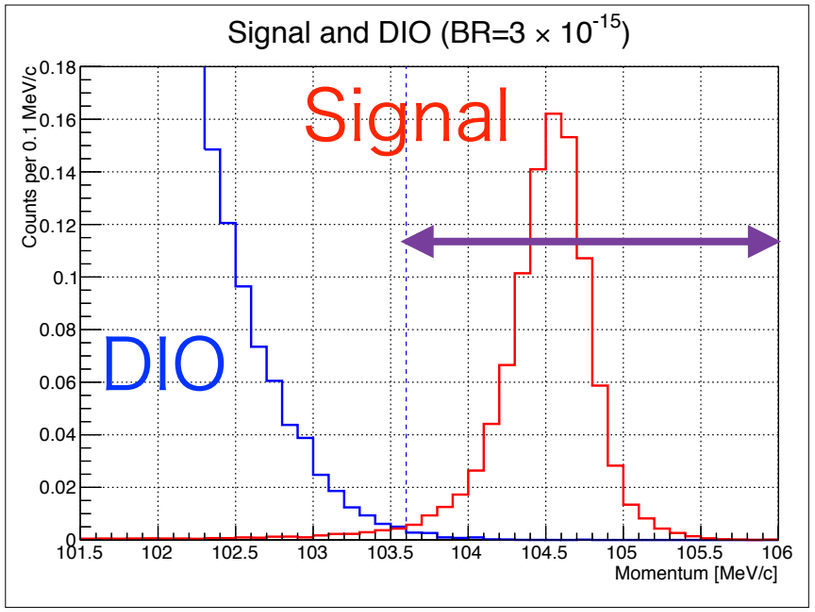


Event Display of “μ-e conversion” generated with ICEDUST

Sensitivity Estimation in COMET Phase-I

Signal Acceptance

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
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3
Total	0.041



Signal Sensitivity

- f_{cap} = 0.61, f_{gnd} = 0.9
- $A_{\mu e}$ = 0.041
- N_{μ} = 1.5 x 10^{16} muons

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

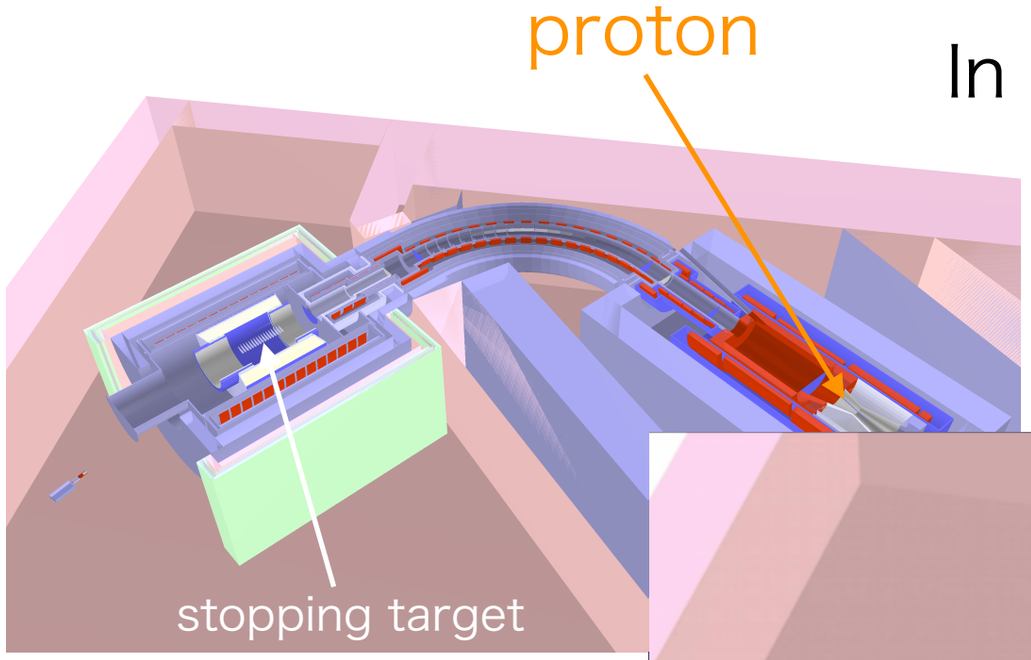
$$B(\mu^- + Al \rightarrow e^- + Al) = 3 \times 10^{-15} \quad (\mathrm{S.E.S})$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \quad (90\%C.L.)$$

Muon intensity

about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 150 days is needed.

toward COMET Phase-II

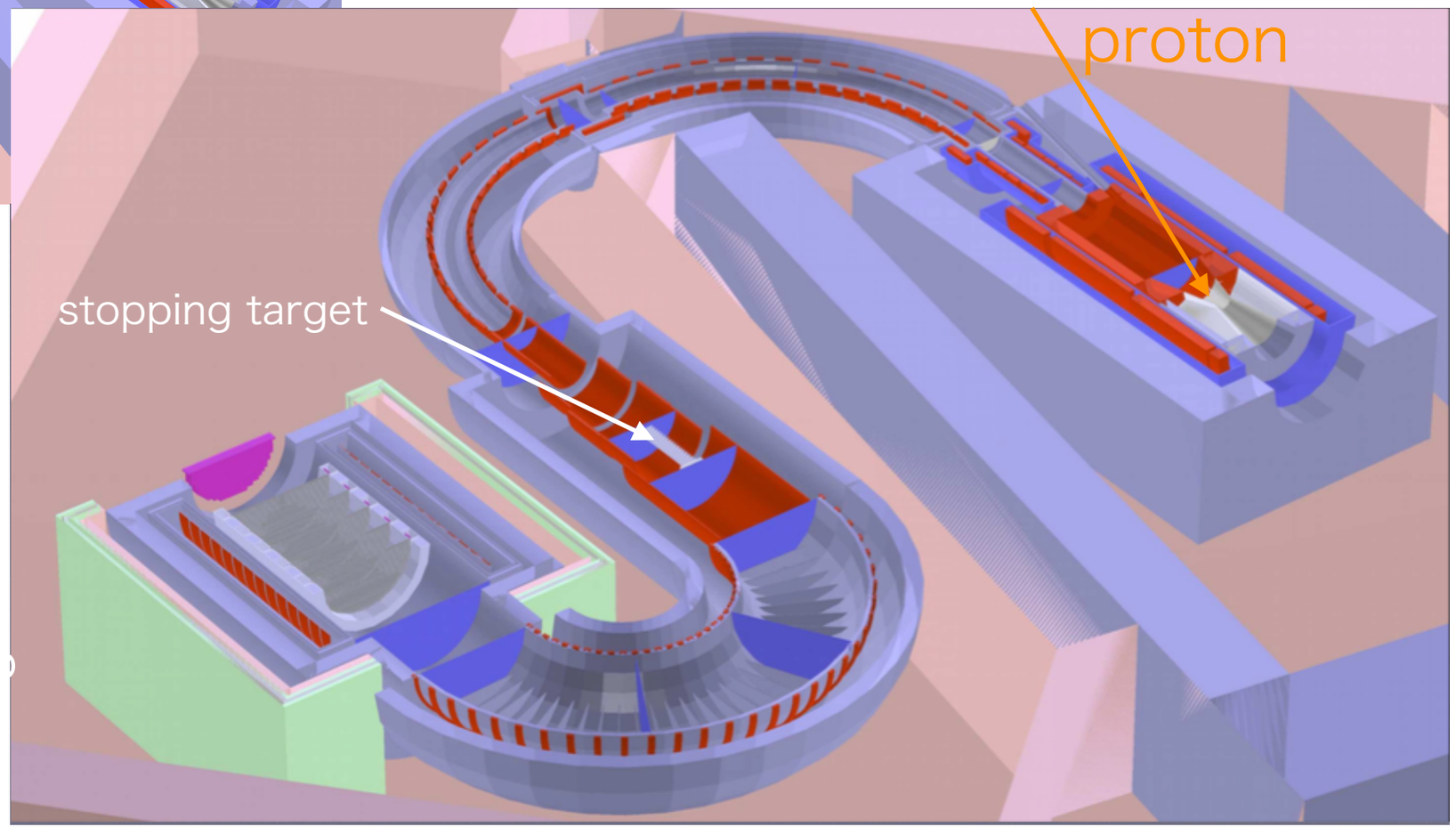


In Phase-I setup

- 3.2 kW proton beam operation
- 90 degree muon transport solenoid
- CDC in a spectrometer solenoid

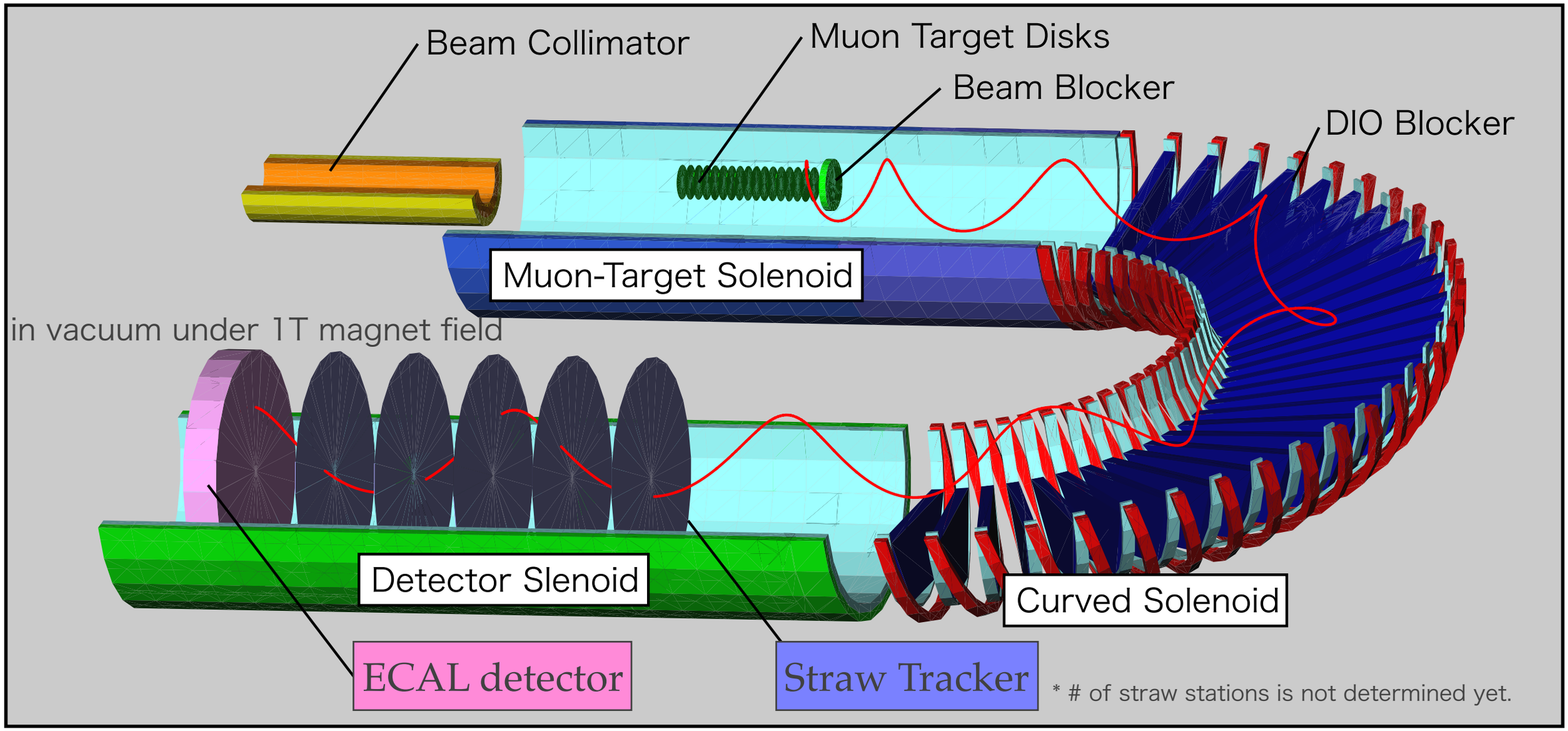
In **Phase-II** setup

- 56 kW proton beam
- new W Proton target (C target in Phase-I)
- 180 degree transport solenoid for muon
- 180 degree spectrometer solenoid for electron
- StrawECAL detector



S-Shape Design in Phase-II

Phase-II Detector



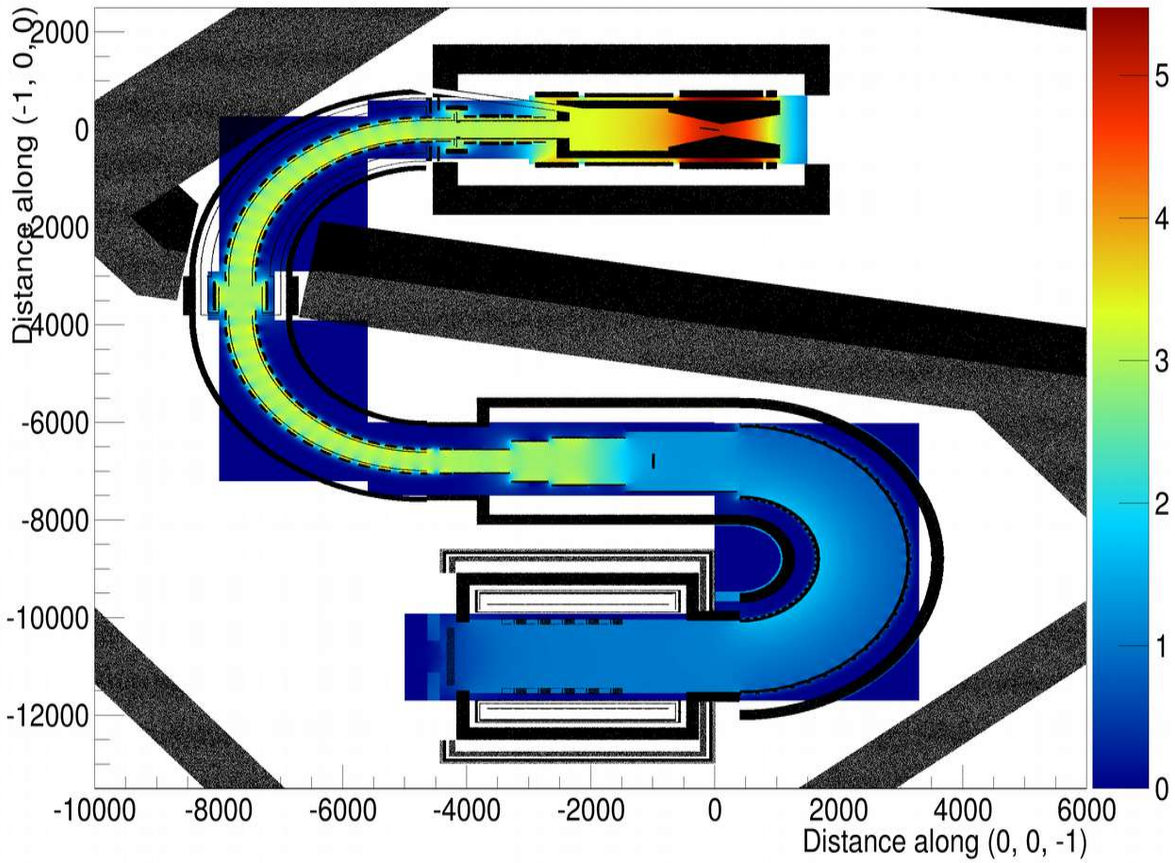
- 180° curved solenoid for higher momentum resolution in the muon/electron transport
- Less dense detectors (Straw Tracker and ECAL in vacuum)

Phase-II Goal :
(in a year operation)

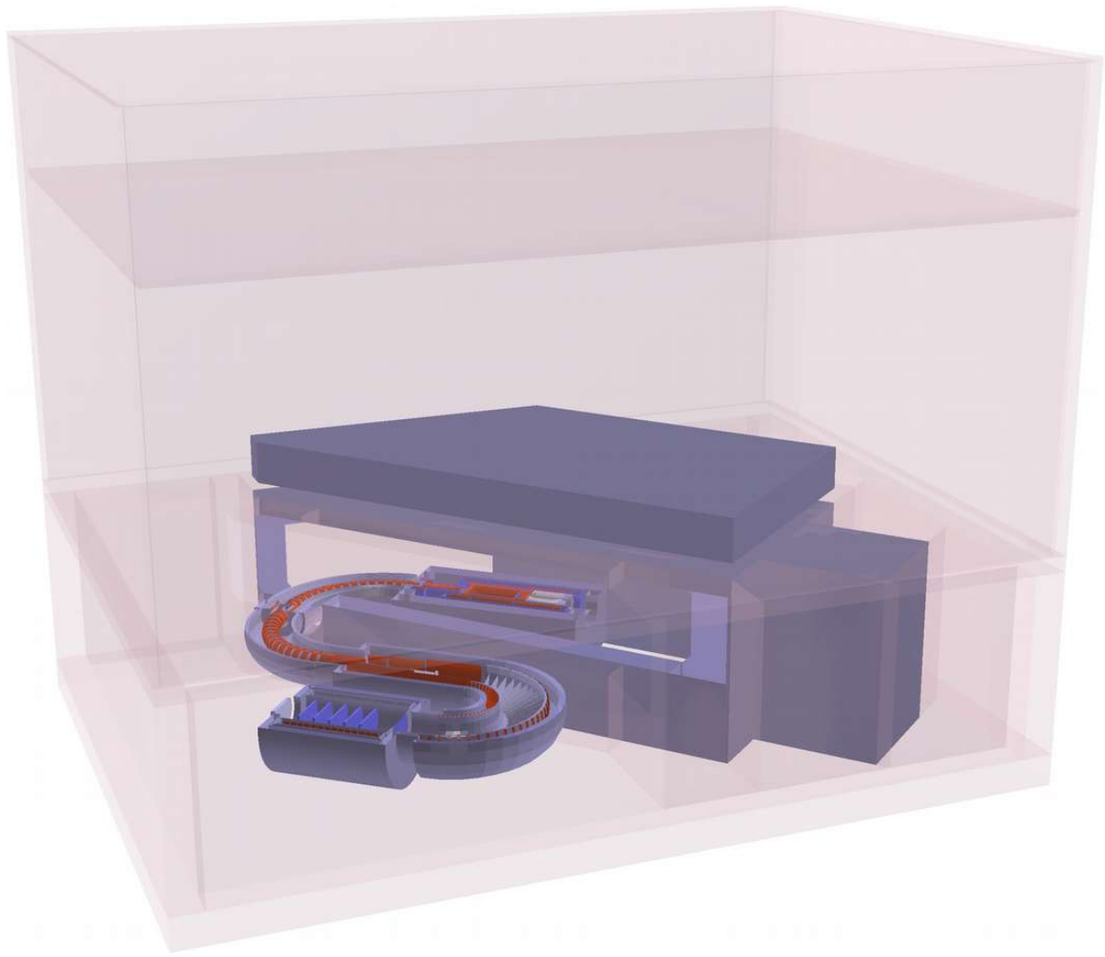
$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17} \ (\mathrm{S.E.S})$$
$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

Status of COMET Phase-II

- Development of Phase-I StrawECAL is essentially R&D for Phase-II
- ICEDUST framework enables feasible study for Phase-II



field map design for Phase-II



simulation setup for Phase-II

- Working for further foundation in Phase-II, and negotiating with J-PARC facility for operation schedule for Phase-II

Summary

- COMET is an experiment search for "μ-e conversion" at J-PARC
  - aiming improvement the sensitivity x 10,000 better than the past
  - staging approach called Phase-I (under construction) / Phase-II
- **COMET Phase-I** is now under construction
  - aiming improvement the sensitivity x 100 better than the past

Phase-I Goal :
(in 150 days operation)

$$B(\mu^- + Al \to e^- + Al) = 3.0 \times 10^{-15} \ (\mathrm{S.E.S})$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

  - CDC detector for physics search is under commissioning now
  - the other system is also under construction
  - will be **ready in 2019,** stay tuned! http://comet.kek.jp/

- R&D for **COMET Phase-II** is underway.
  - expecting to start in 202X?, aiming further higher sensitivity