The COMET Experiment at J-PARC

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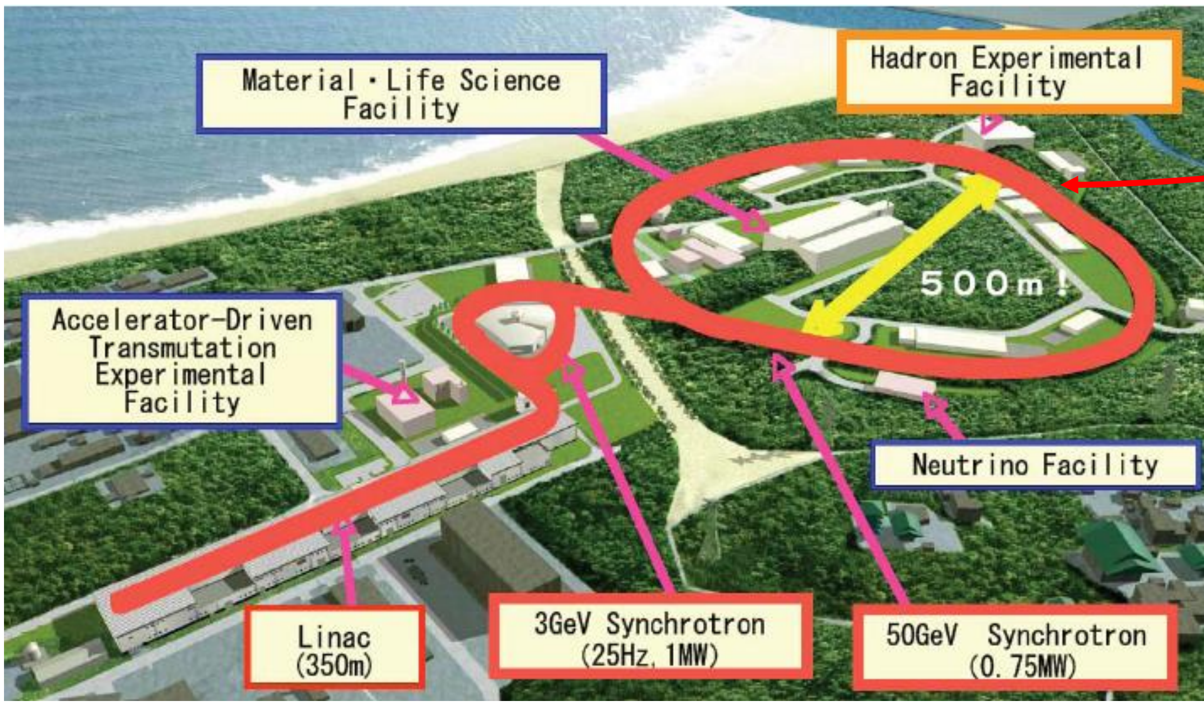
Outline

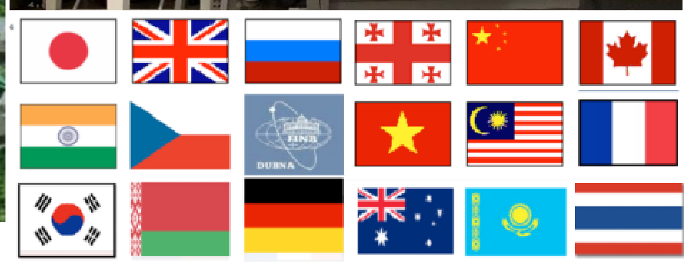
- About COMET
- Physics Motivation
- Design of the COMET Experiment
- Current Status of the COMET Experiment
- Summary

About COMET

COMET: COherent Muon Electron Transition

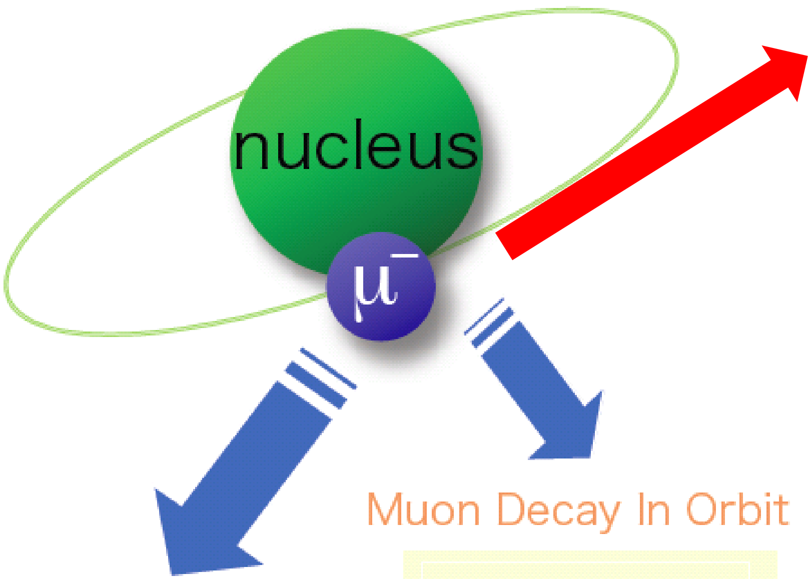
- Utilizing the proton source from J-PARC main ring, COMET searches for muon to electron conversion process which violates charged lepton flavor conservation: $\mu^- N \rightarrow e^- N$
- An international collaboration.
  - 41 institutes from 18 countries. ~200 members.





COMET searches for $\mu - e$ conversion

1s state in a muonic atom



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

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

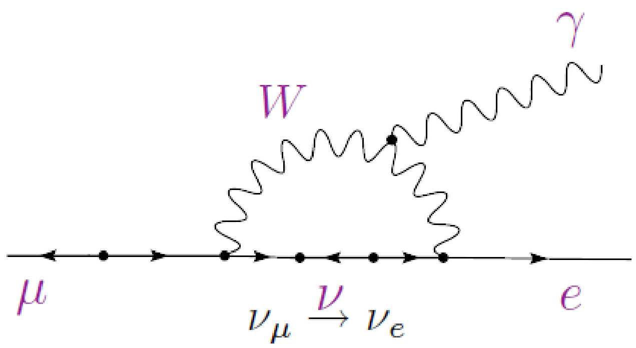
Charged lepton flavor violated

Conversion rate: $CR(\mu^- N \rightarrow e^- N) \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \text{all})}$

- **Signal signature:**
  - Mono-energetic electron with energy of 105 MeV
- **Background signature:**
  - No accidental background
    - Luminosity frontier
  - Beam background can be suppressed by pulsed beam
  - Physics background can be handled with current detector technology

Physics Motivation

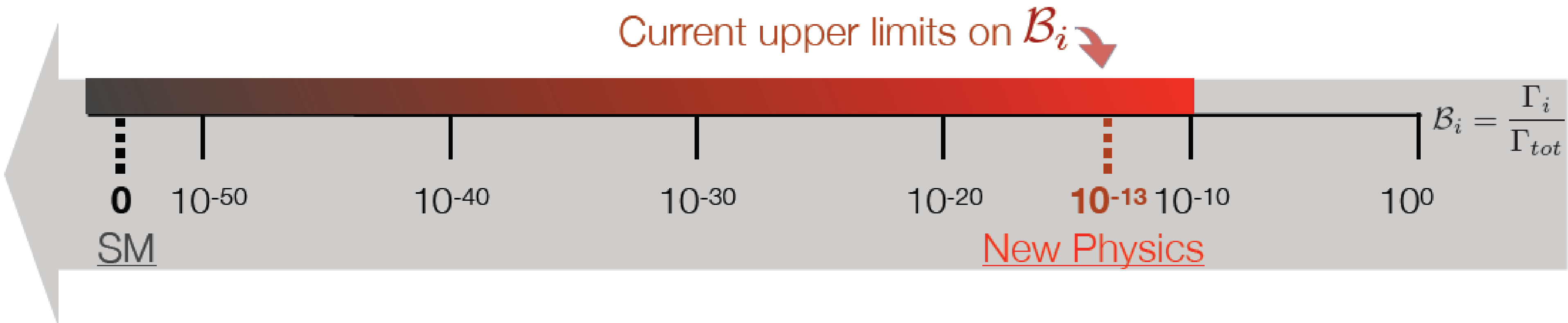
Charged Lepton Flavor Violation



cLFV highly suppressed in SM+m_ν:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

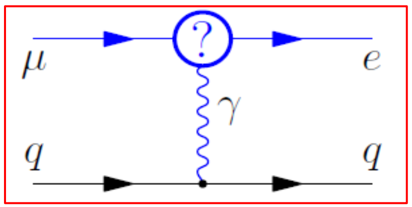


Clean field to search for new physics!

Exloring high energy scale with $\mu - e$ conversion

Extend SM in effective field theory with Dim-6 operator: $\mathcal{L} = \mathcal{L}_{SM} + \sum_{n\geq 2} \frac{C^{4+n}}{\Lambda^n} \mathcal{O}^{4+n}$

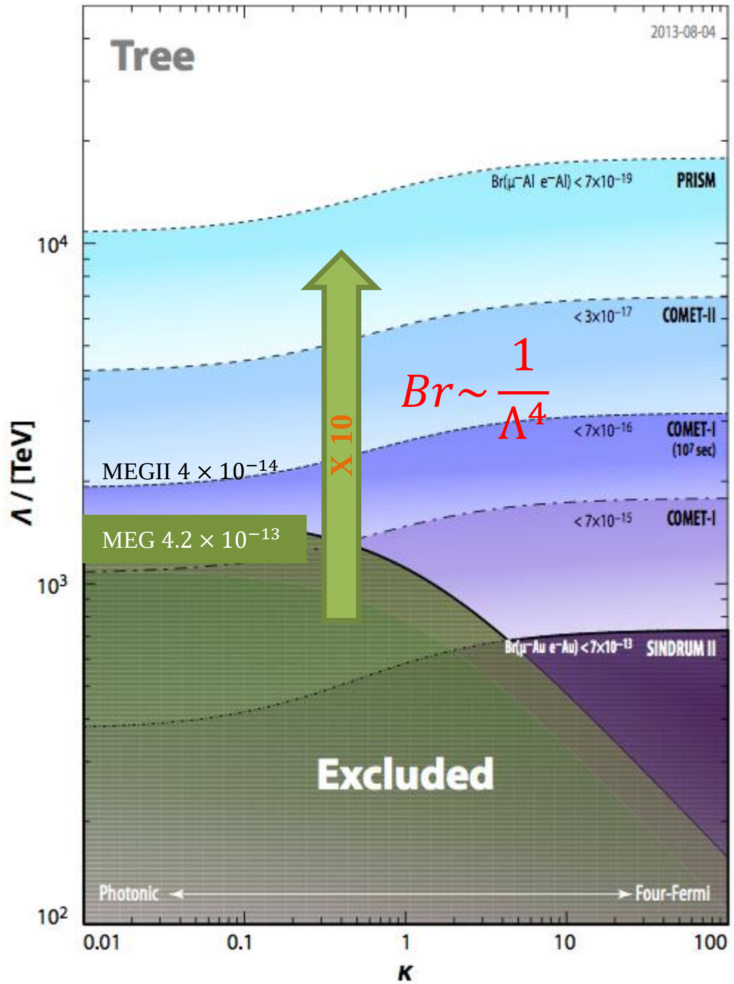
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma_\mu q_L$$

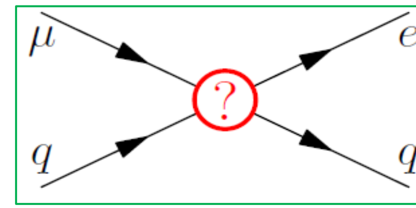


Photonic process

$\kappa \ll 1$

$\mu \to e\gamma$	$\mu - e$
Strong	Sizable





Four-Fermi process

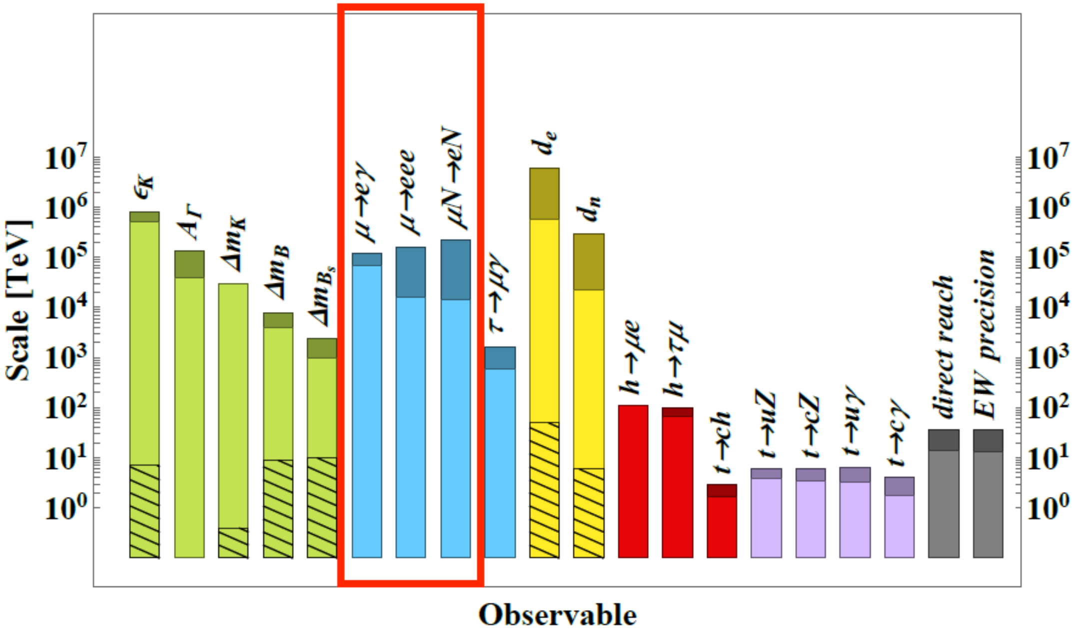
$\kappa \gg 1$

$\mu \to e\gamma$	$\mu - e$
None	Strong

$\mu - e$ conversion can test two different processes.

New Physics Scales for CLFV

Light color: present
Dark color: future prospect



EPPSU2019 Physics Briefing Book

For $\mu - e$ conversion:

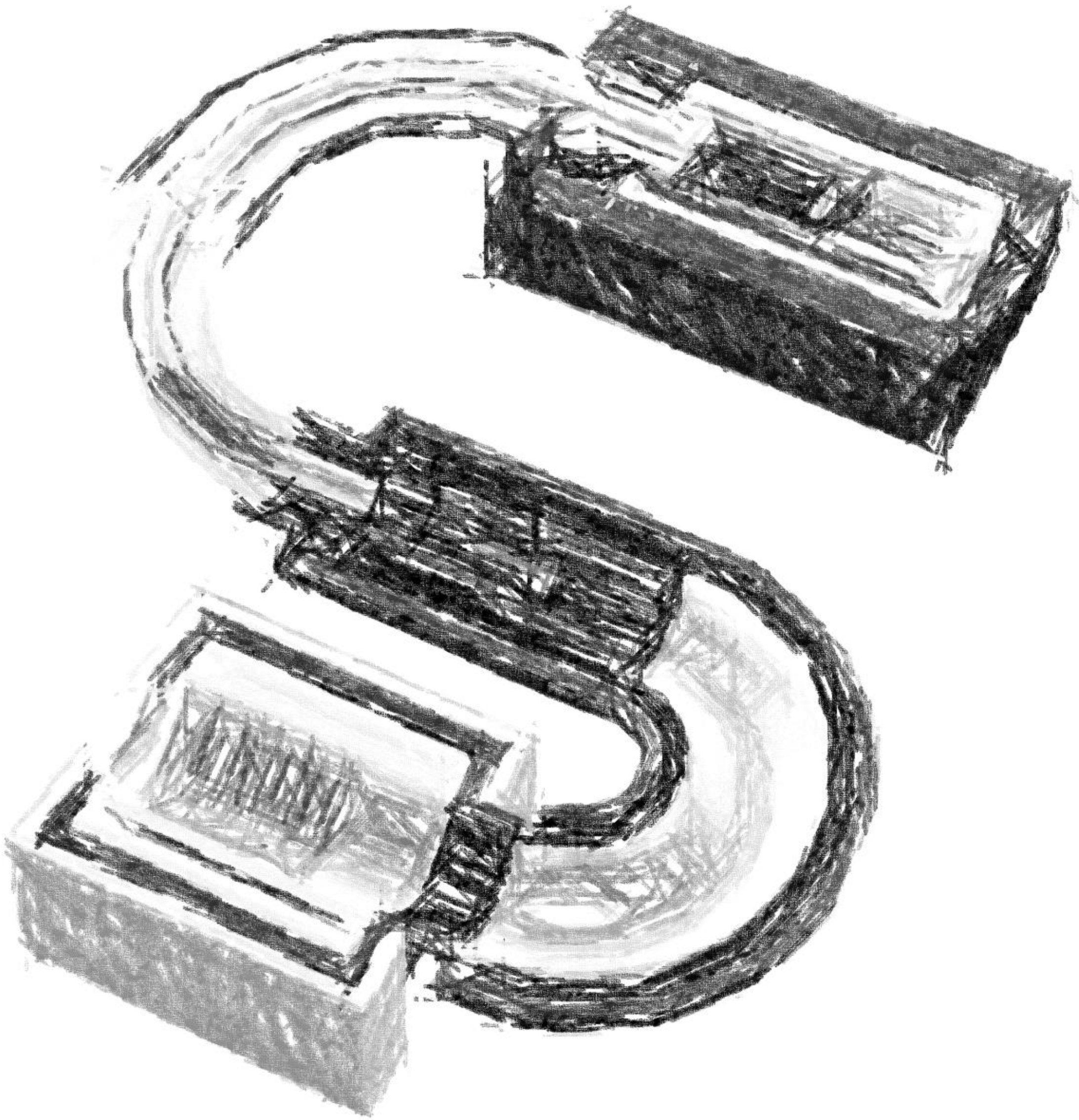
- Current limit:

nucleus	Z	CR limit
sulfur	16	7×10^{-11}
titanium	22	4.3×10^{-12}
copper	39	1.6×10^{-8}
gold	79	7×10^{-13}
lead	82	4.6×10^{-11}

SINDRUM II Collaboration, Phys. Lett. B, 422 (1998) 334.
SINDRUM II Collaboration, Eur. Phys. J. C 47 (2) 337-346 (2006)
SINDRUM II Collaboration, Phys. Rev. Lett., 76 (1996) 200.y

- We aim to improve the sensitivity by a factor of 10,000!

Design of the COMET Experiment



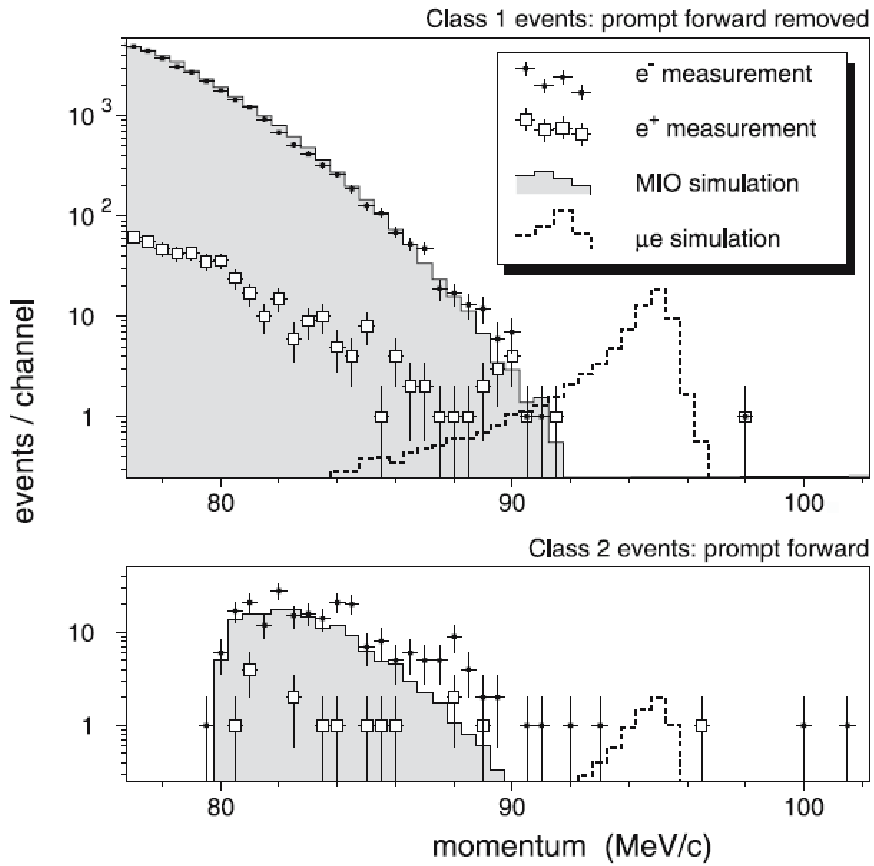
Lesson from SINDRUM-II

PSI proton beam repetition rate: 50.6 MHz.
Pion lifetime: 26 ns

- Pions can survive between pulses
- SINDRUM-II strategy:
    - Use narrow momentum window and time window to select the beam.
    - Highly relying on the understanding of the beam
- Found unexpected events and had to stop.

To move forward, pulsed beam with large separation time is needed!

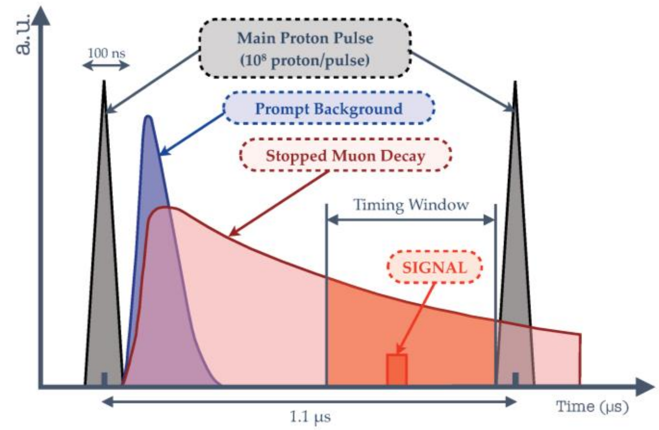
- If the detector can wait ~700 ns after the pulse, the pion survival rate will be 10^{-9} (time dilation not considered)



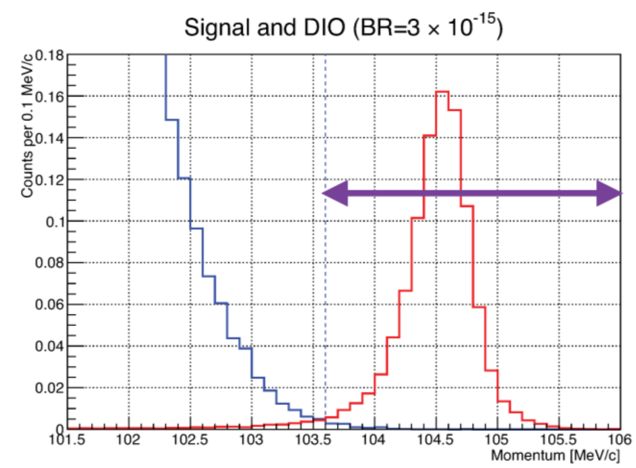
Eur. Phys. J., 2006, C47:337-346

Towards $< 10^{-16}$ sensitivity

- Need much more muons
  - Thick proton target: ~1 hadron interaction length.
  - Powerful capture magnetic field. ~5 T
- Need to suppress pion induced background
  - Pulsed beam. Wait for pion decays.
- Need to suppress other beam particles
  - Curved solenoid: select low momentum.
  - Pulse beam also helps: wait for fast particles fly through.
- Need to control muon decay in orbit (DIO) background
  - 200 keV/c resolution can work: drift chamber, straw tracker, etc.
  - Mind the non-gaussian tail: fitting quality check.
- Need to suppress cosmic ray induced background.
  - Pave scintillators on top to veto cosmic ray event.
  - Reduce live time: higher beam intensity.

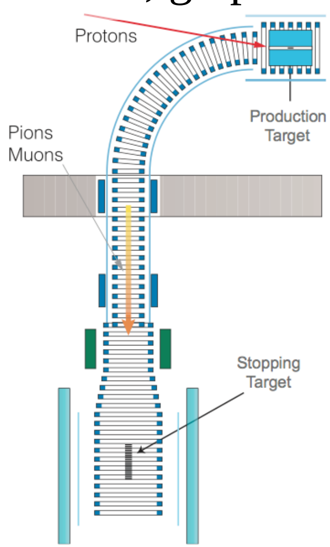


*Trade off: can't use high-Z target



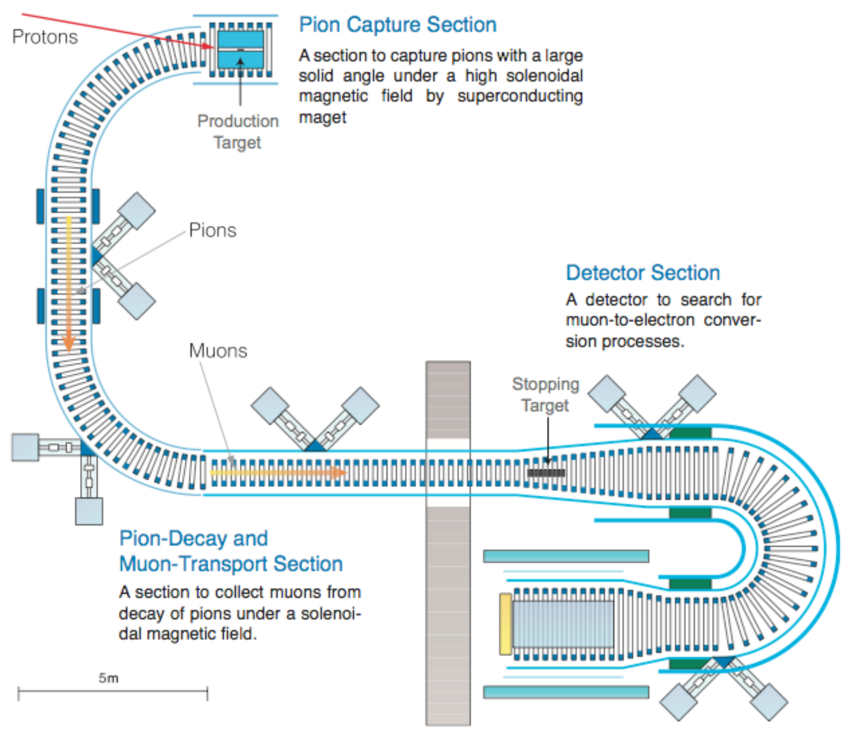
COMET @ J-PARC

COMET Phase-I
- Directly measure the muon beam with prototypes of Phase-II detector.
- Search for $\mu - e$ conversion with factor of 100 improvement
- LOI submitted in 2011: E21
- 8 GeV, 3.2 kW, graphite target

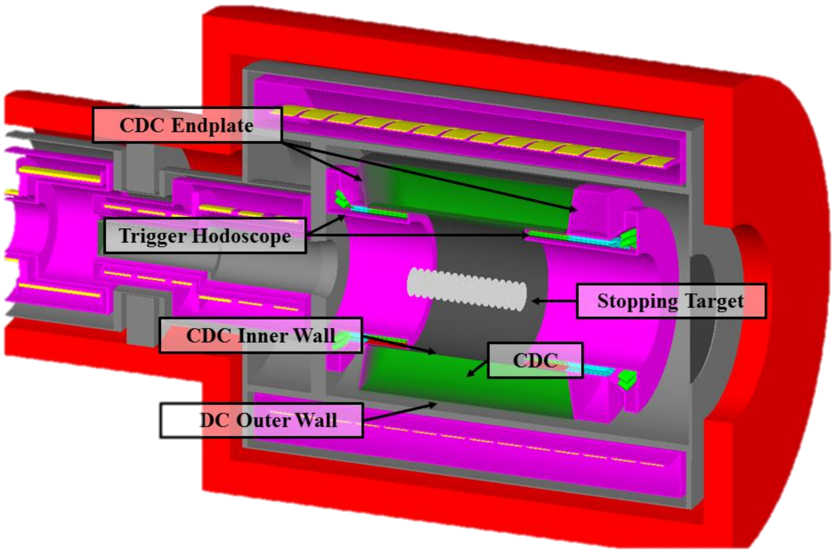


- Upstream part same as Phase-II
  - Except production target and part of shielding
- Detector is different, like CDC.

COMET Phase-II
- Search for $\mu - e$ conversion with full sensitivity: factor of 10,000 improvement
- CDR submitted in 2009
- 8 GeV, 56 kW, tungsten target

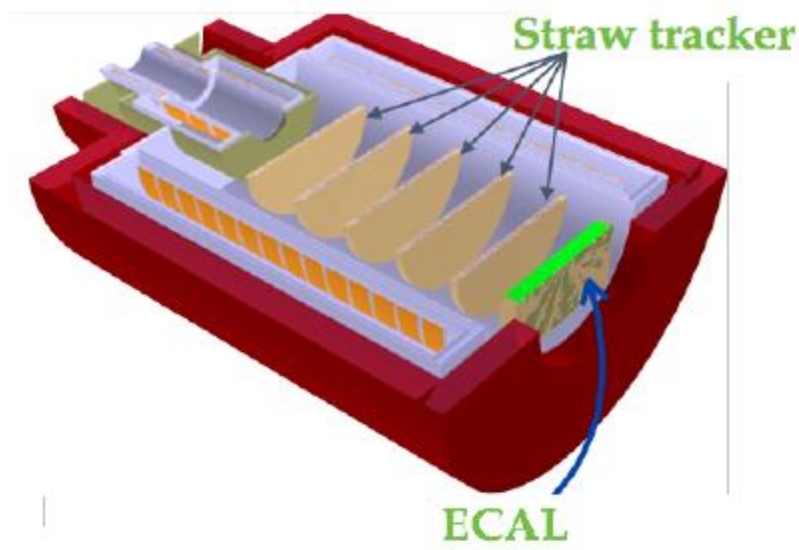


Phase-I detector: Cylindrical detector (CyDet)



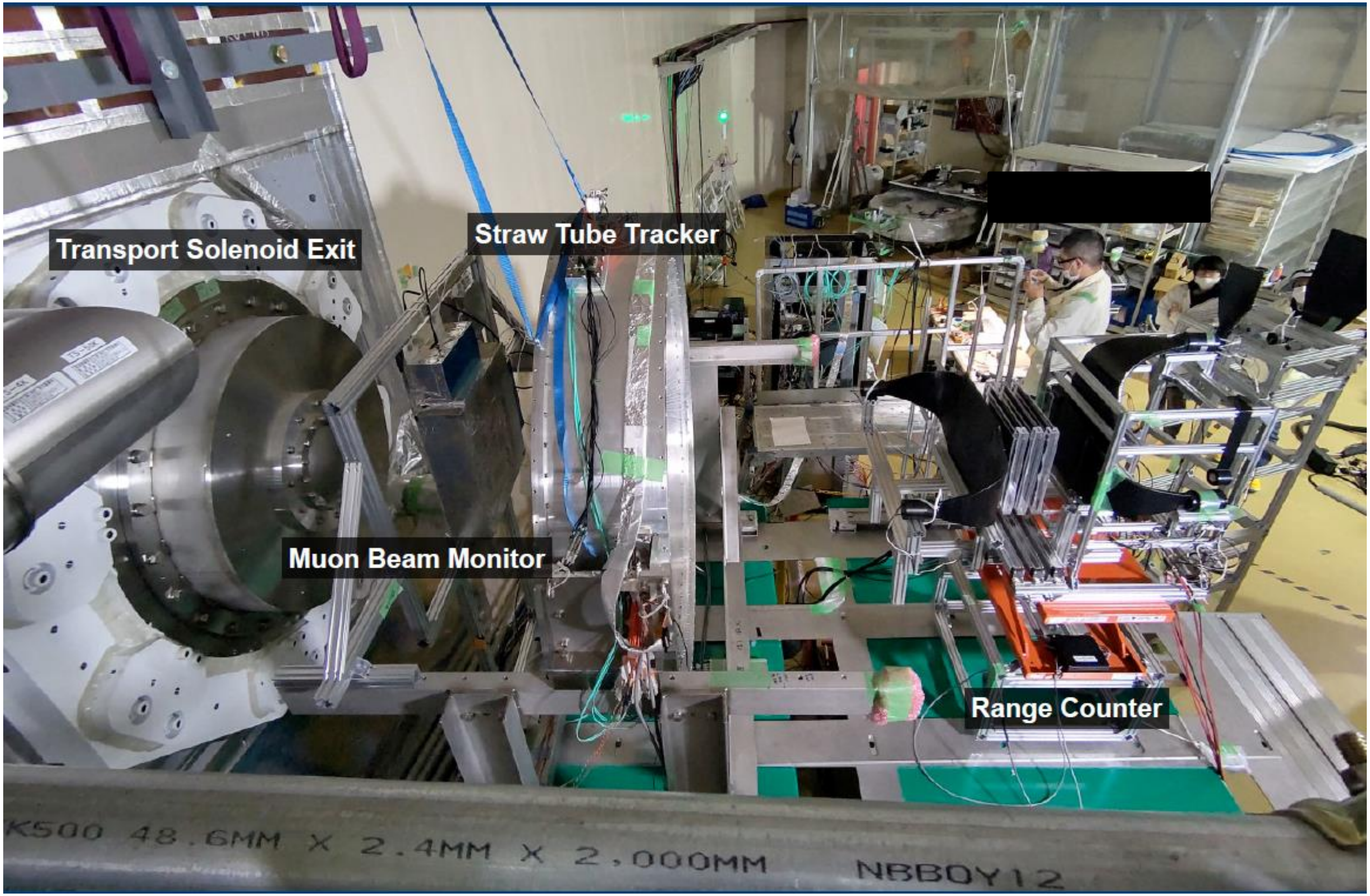
- Specially designed for Phase-I. Consists of:
  - Cylindrical trigger hodoscope:
    - Two layers of plastic scintillator for t0 and later replaced by Cerenkov counter for PID.
  - Cylindrical drift chamber:
    - All stereo layers: z information for tracks with few layers' hits.
    - Helium based gas: minimize multiple scattering.
    - Large inner bore: to avoid beam flash and DIO electrons.

Phase-I detector: Straw Tracker & Energy Calorimeter (StrEcal)



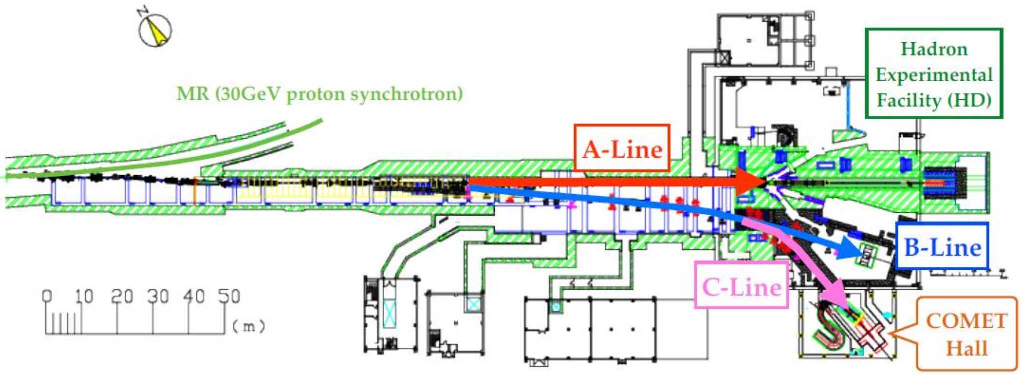
- To measure all delivered beam incl BG, vacuum-compatible tracker and calorimeter is employed
- Straw = Planer/Low-mass, LYSO crystal ECAL = High resolution / High density
- Same concept as Phase-II detector = Prototype of Phase-II Final Detector

Current Status of the COMET Experiment



COMET Facility

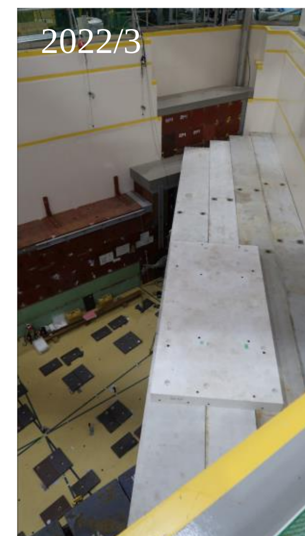
C-line ready. Proton beam came to COMET for the first time.



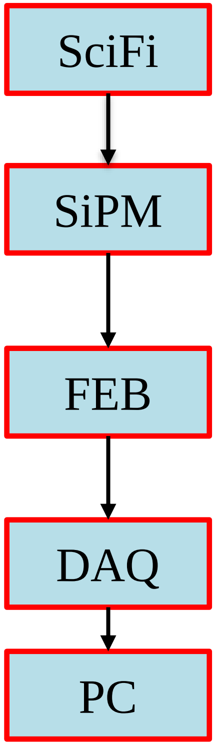
Detector area prepared in 2022.

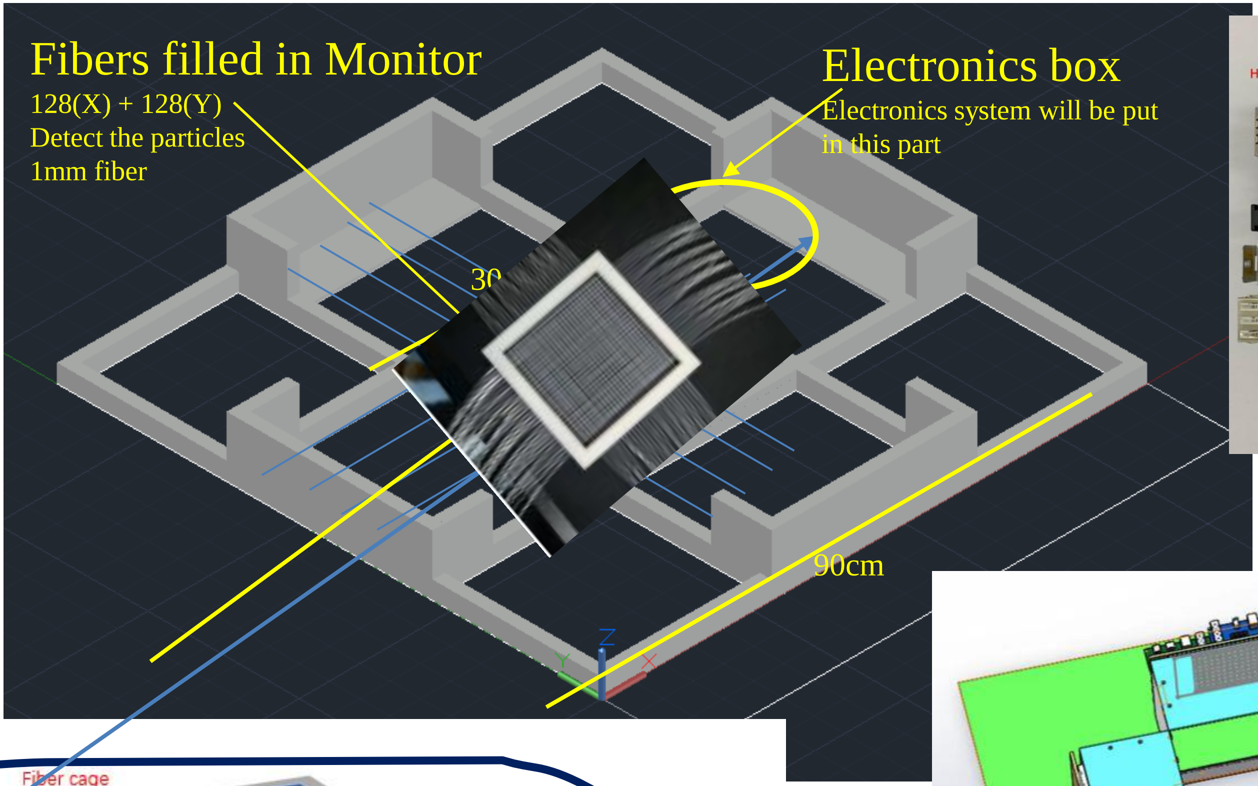
MTS (muon transportation solenoid) in position.

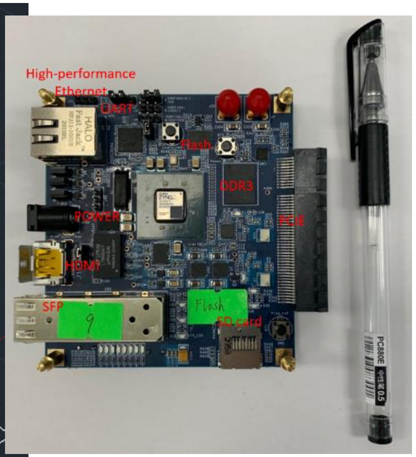
Shielding added last year.

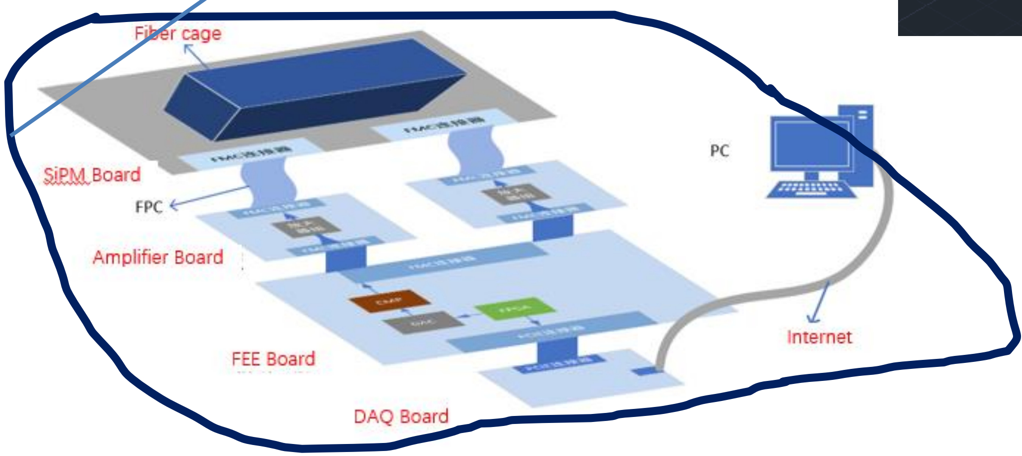


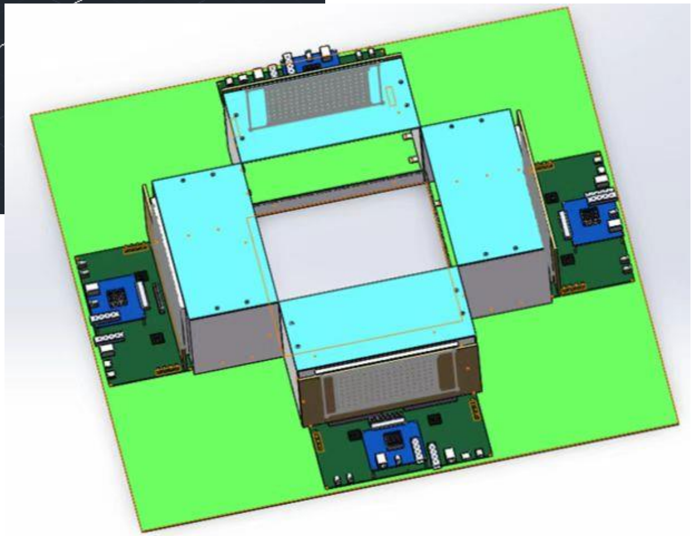
Development of MBM



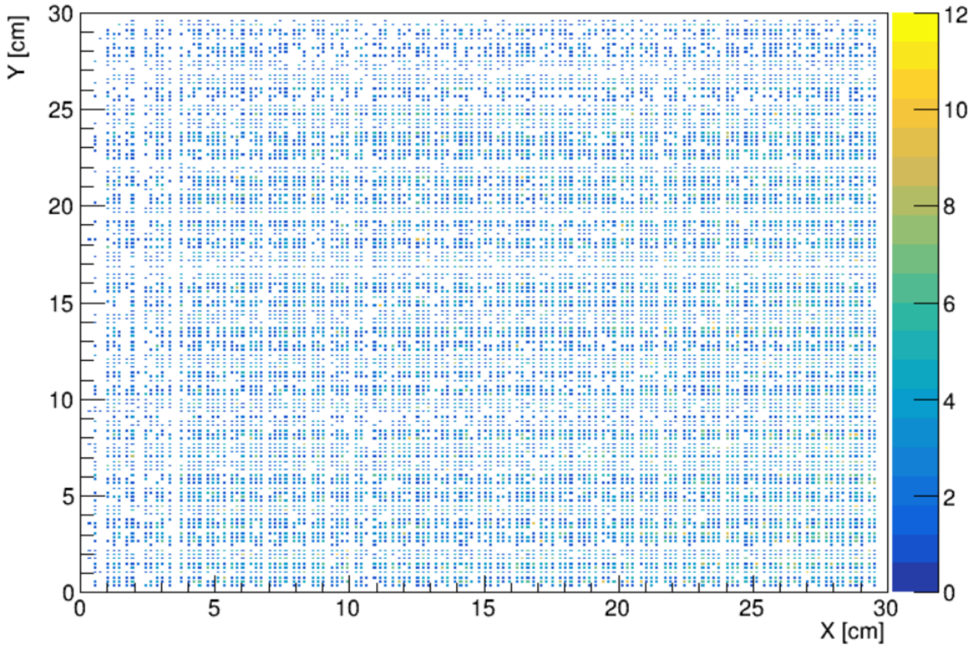


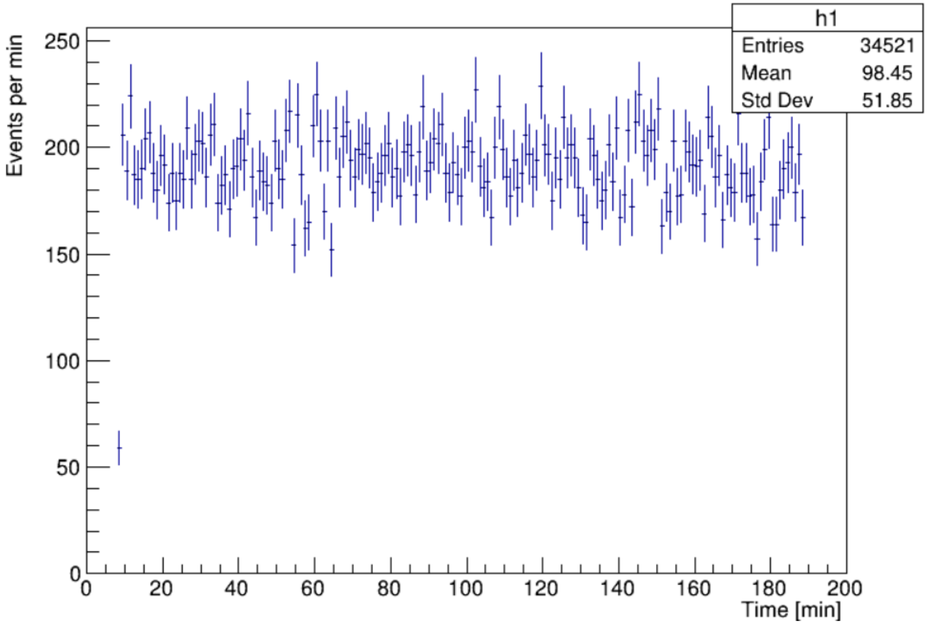






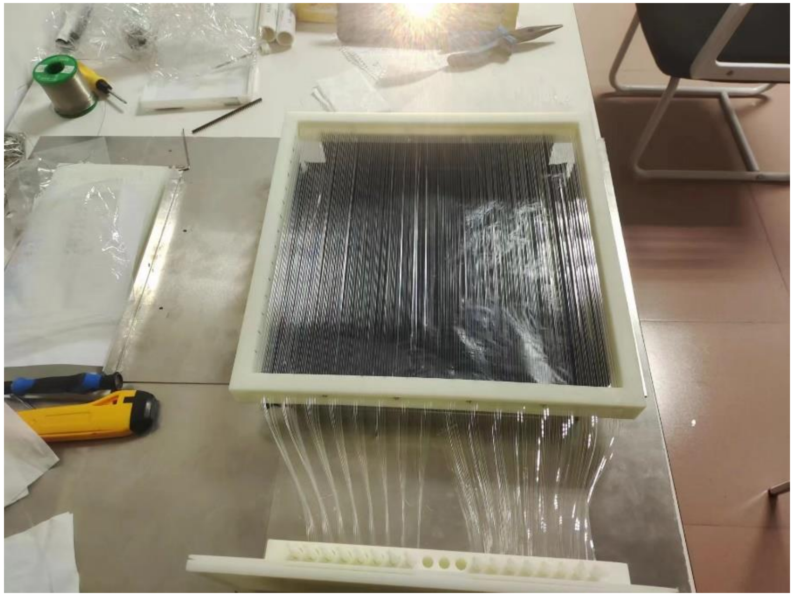
Development of MBM

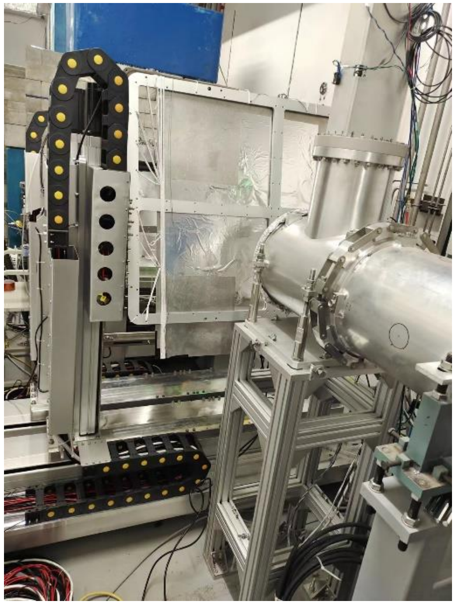


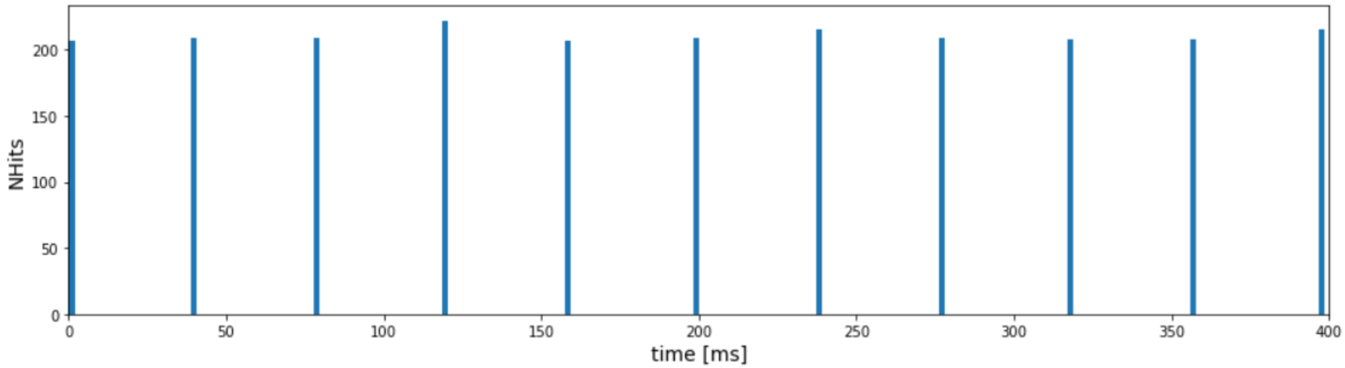


- 3 hours data taken in the SMOOTH laboratory
- 2D plot for cosmic muon
- Cosmic muon trigger rate vs time

Development of MBM







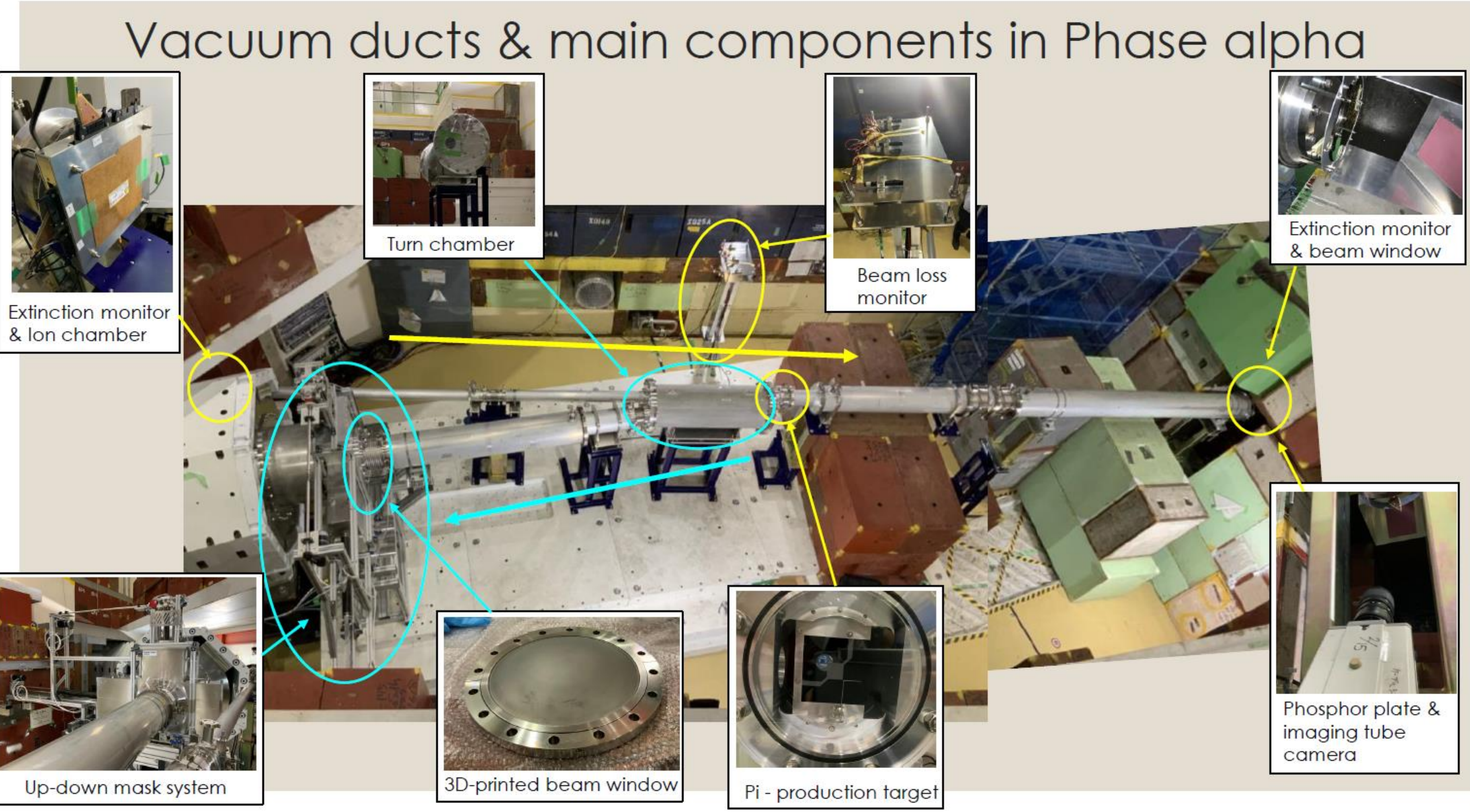
Proton beam tests, July 20th in 2022@CSNS

COMET Phase α

- A demonstration of the muon beamline with the transport solenoid but without the capture solenoid, so-called "Phase-alpha", was carried out from February to March in 2023.
    - A low beam-intensity (0.26 kW) run to study the muon beam, with 1 mm thick graphite target.
- For the first time, the proton beam arrived at the COMET experimental hall, and muons were observed!

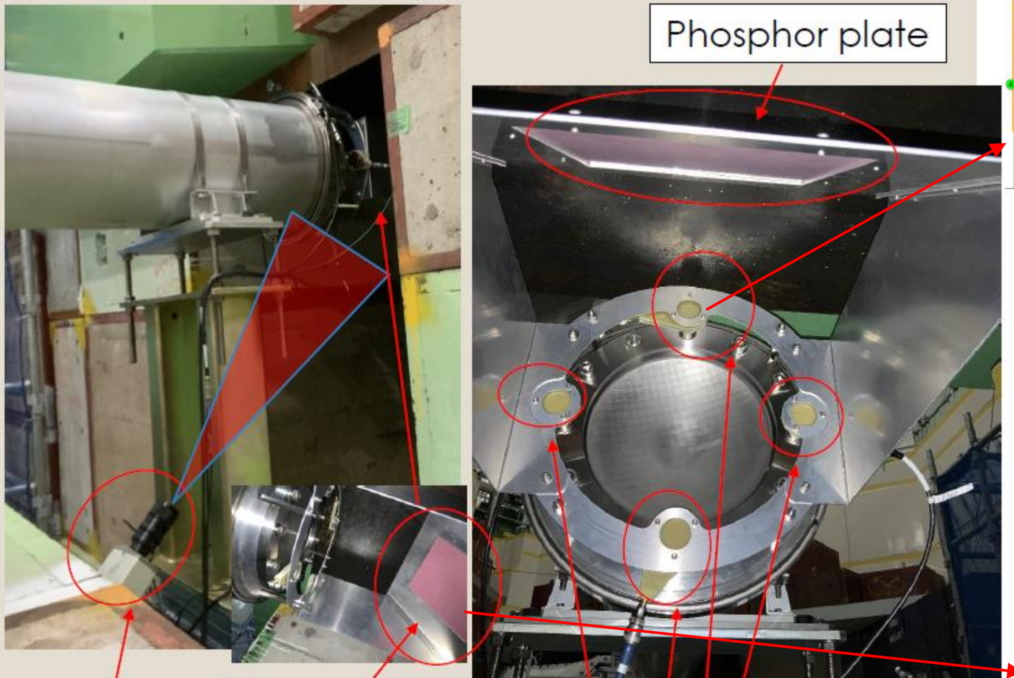
COMET Phase α

A series of different measurements were carried out by the collaboration among different international groups.



Proton beam measurement

Exit of proton beam
- 4- Extinction monitors by Pradeep group
- Phosphor plate – imaging tube camera by hadron beamline group



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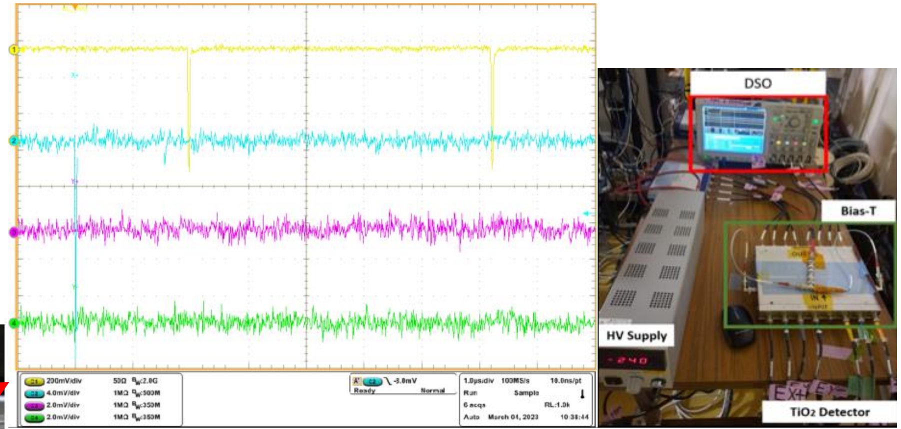
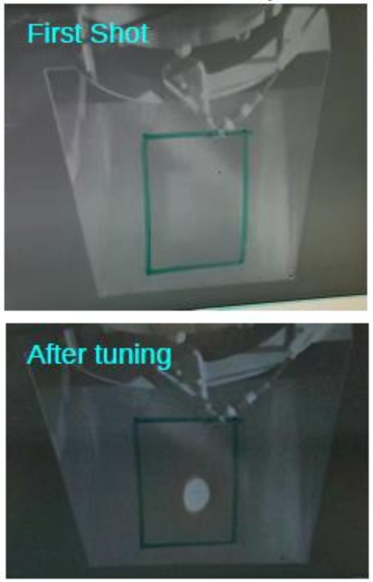
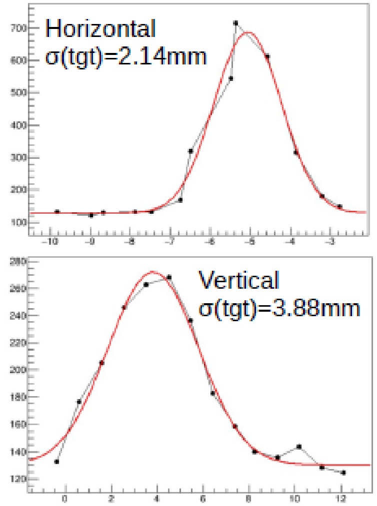
TiO2 detector

Pulse likely to be proton hits detected.

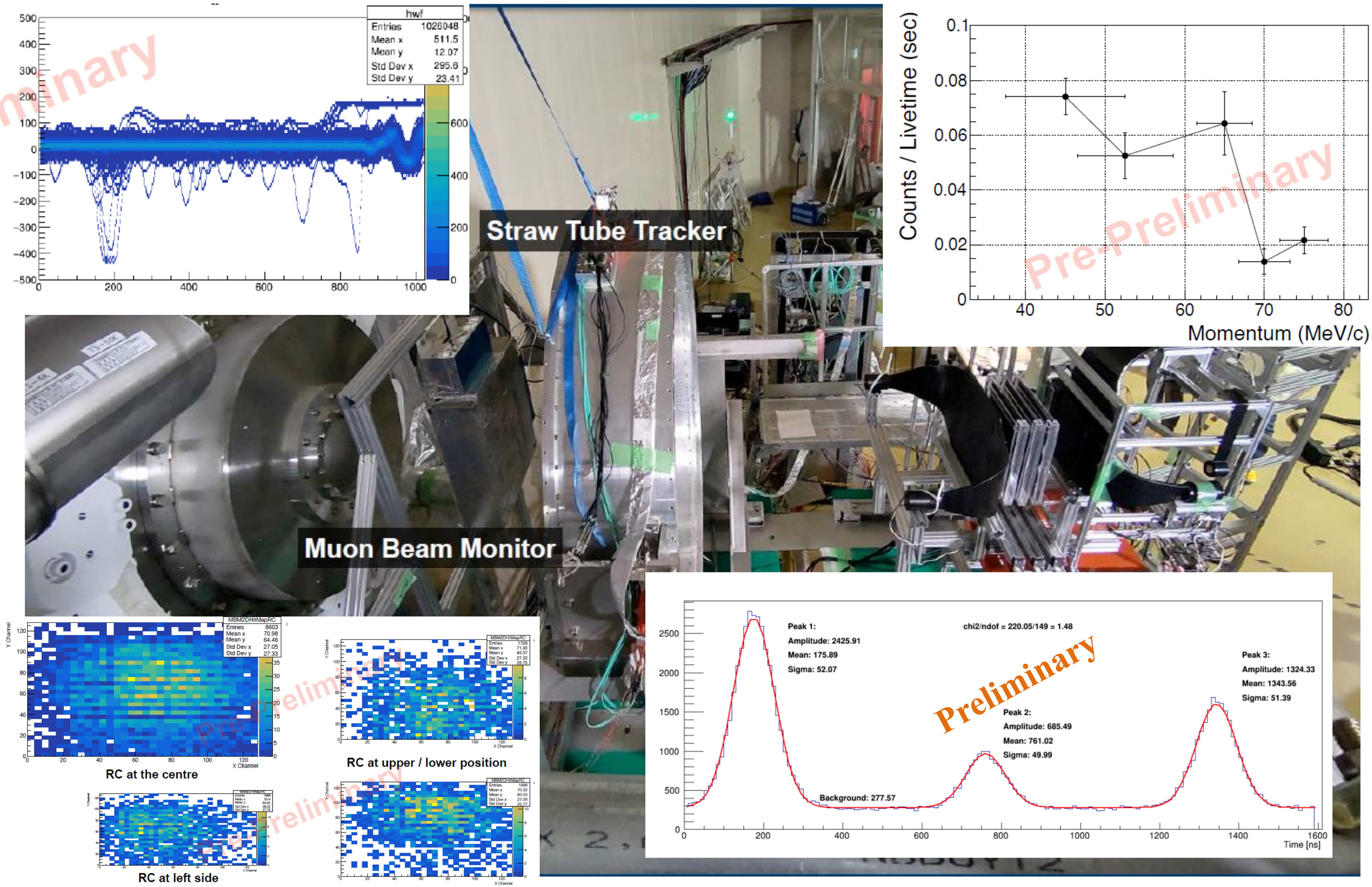


Focused the beam, and measured the size.



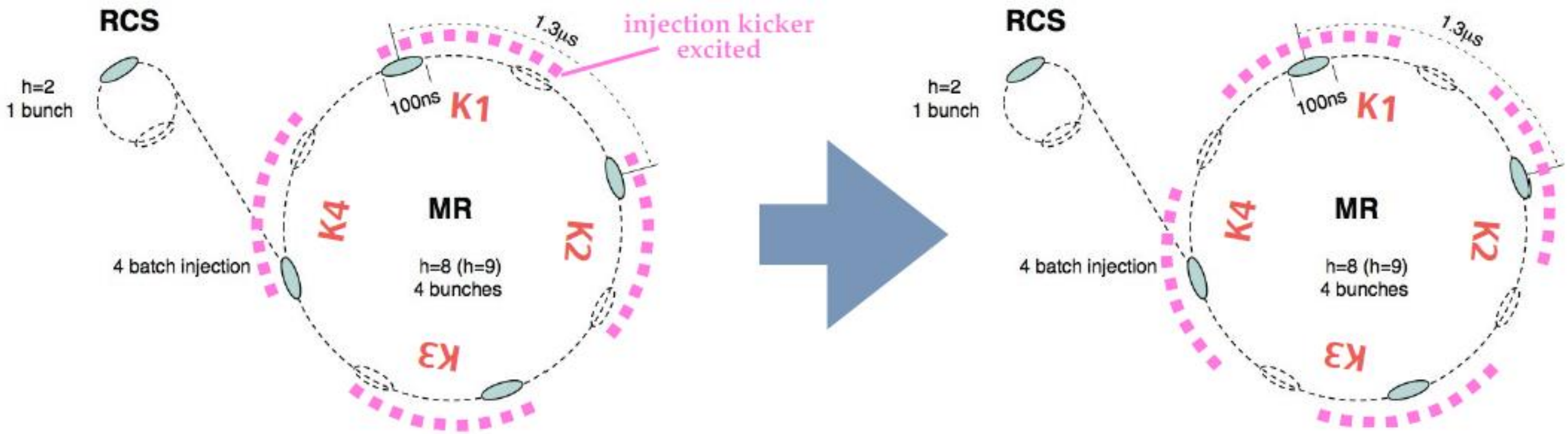


Muon beam measurement

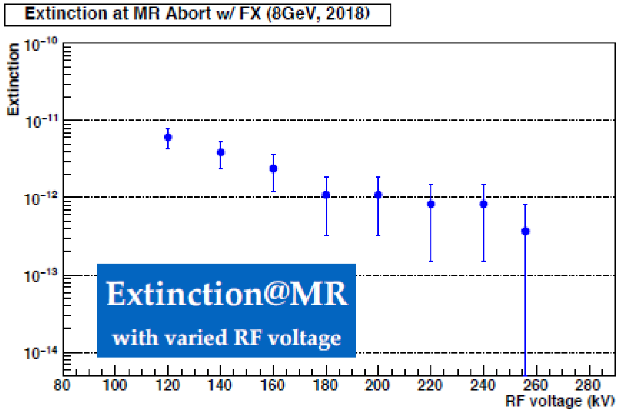


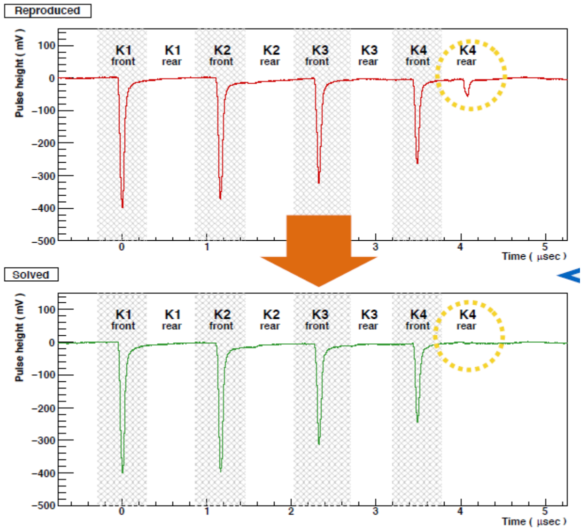
Proton beam from J-PARC

- To make the proton extinction factor: R $(N_{leak}/N_{pulse}) < 10^{-10}$
  - Shift the kicker phase by half period to avoid residual protons in the empty bucket.



Measurement at main ring:
proton leak $< 10^{-12}$

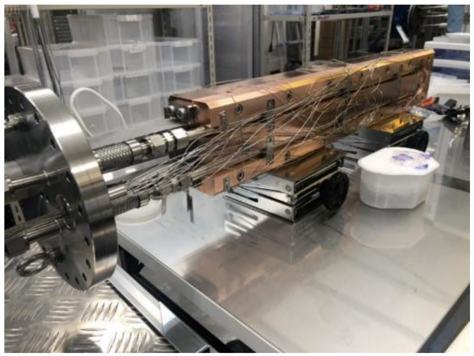




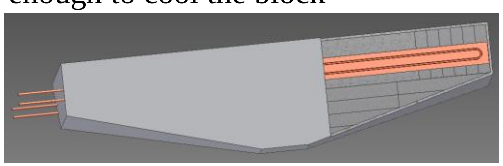
- 2018: Observed K4 rear leak.
- 2021: T78 at hadron hall, solved the leak by shifting the kicker further: $< 1 \times 10^{-10}$
- 2023: Confirmed same performance after the power upgrade in the J-PARC main ring.

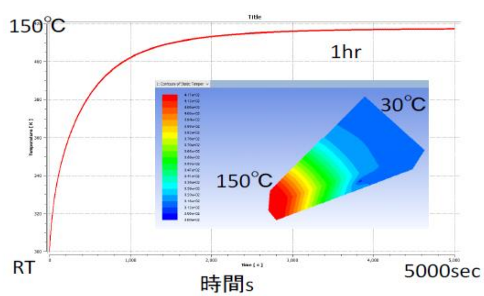
Production Target System

Cooling test of shielding (Cu for Phase-I)

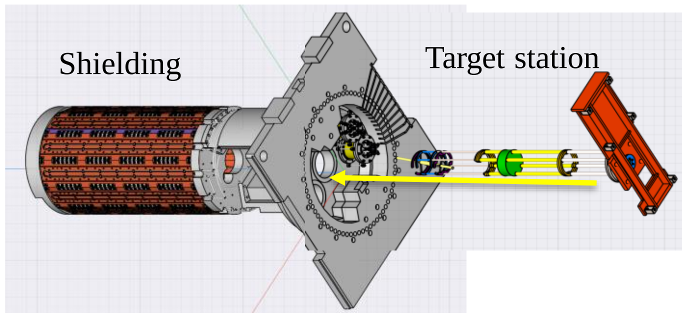


Water cooling for shielding (W for Phase-II): 27 °C 3 m/s inlet water is enough to cool the block

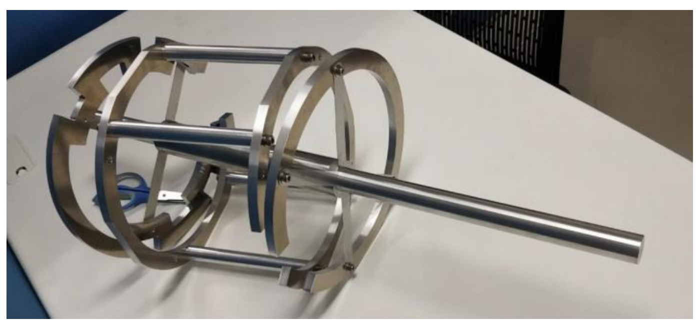




Target station with remote control

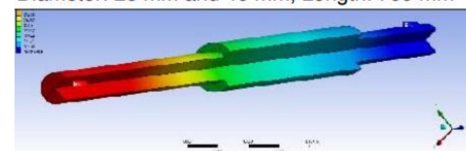


Prototype of target station for Phase-I



Graphite target for Phase-I:
radiation cooling, T<245 degree

Graphite
Diameter: 26 mm and 40 mm, Length: 700 mm



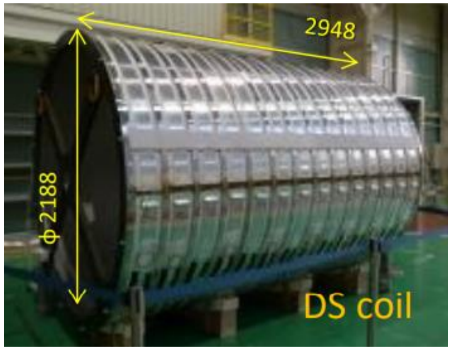
FEM simulation is completed. Max. temp. 245 degC.

Phase-II target needs water cooling.

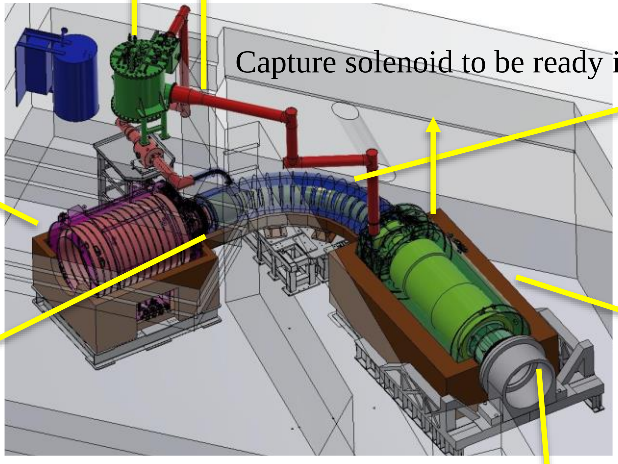
Other materials are being considered…

COMET super conducting solenoids

Coils for the detector solenoid ready in 2015. Whole system to be ready in 2024.



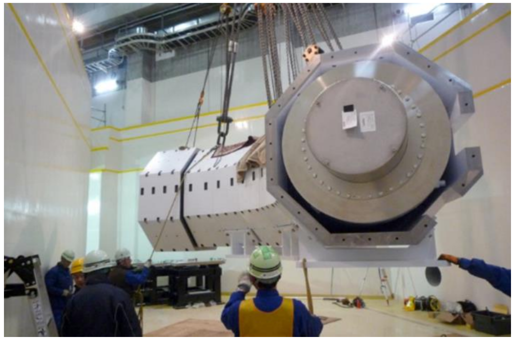
Successfully tested the cooling system with I=3000 A in 2021



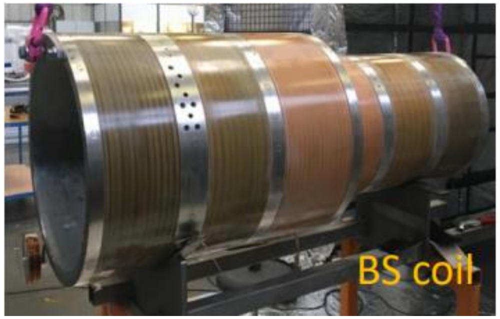
Capture solenoid to be ready in 2024

Installed in 2015. Tested in 2022.
Field map measured in 2022.
Operated with half strength in 2023.

- Due to Eddy current too large.
- Solved by adding extra rods.

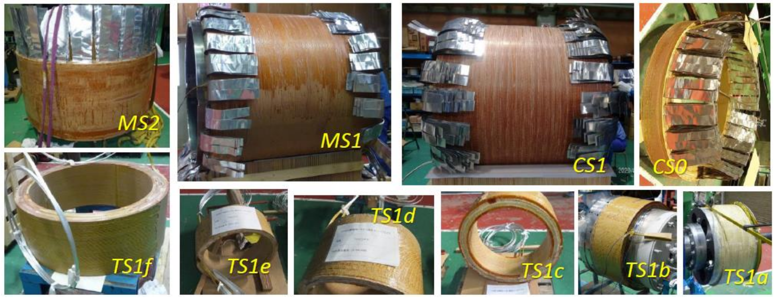


Coils for the bridge solenoid ready in 2018.



Support structure of the capture solenoid ready in 2021

All coils for the captures solenoid ready in 2020



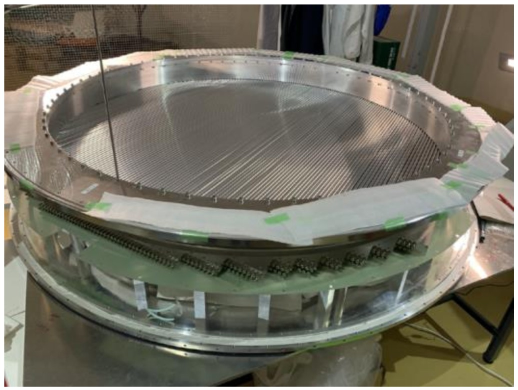
Found degradation of insulation in CS unfortunately:

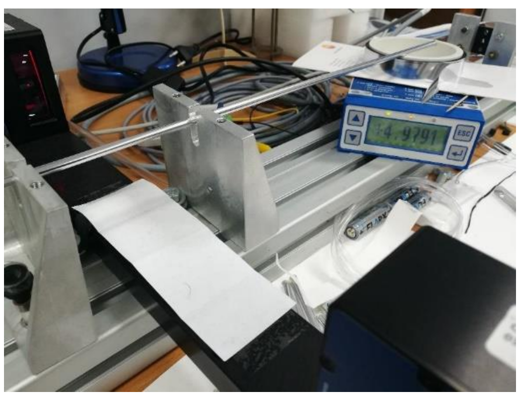
- Location of electric contact identified.
- It will be delivered in March 2024 after fixing the problem…

StrEcal

First station for COMET Phase-I ready. Second station under construction.

- 10 mm diameter, 20 um thickness



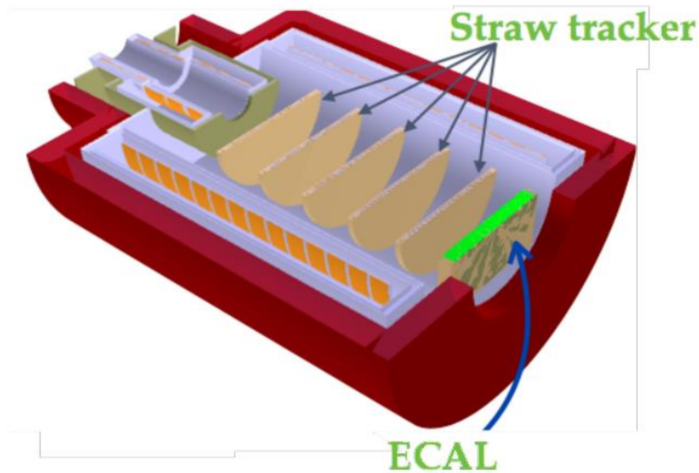


Constructed 5 mm diameter, 12 um thickness straws for Phase-II

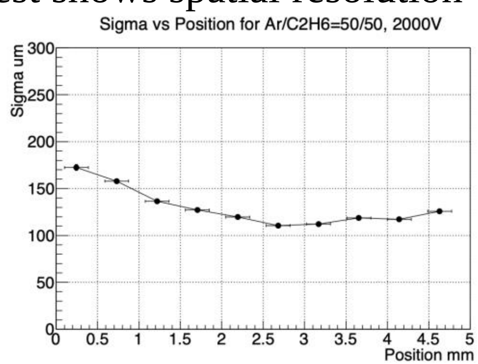
- Pressure tests with 4 bar successful.
- Diameter variation within 120 um
- Further investigations on the way.

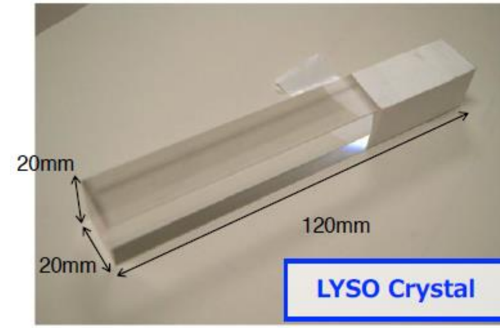
StrEcal system in phase-I: 5 stations and ~500 LYSO crystals.

- In phase-II: more stations, 1920 LYSO crystals



Straw filled with Ar:Ethane=50:50 gas.
Beam test shows spatial resolution~150 um

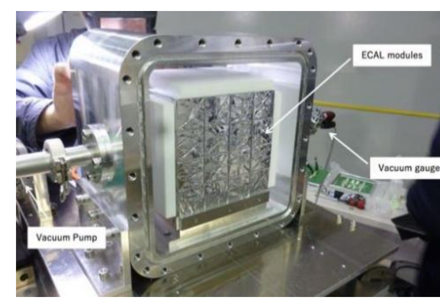




Successful prototype test for LYSO in vacuum.

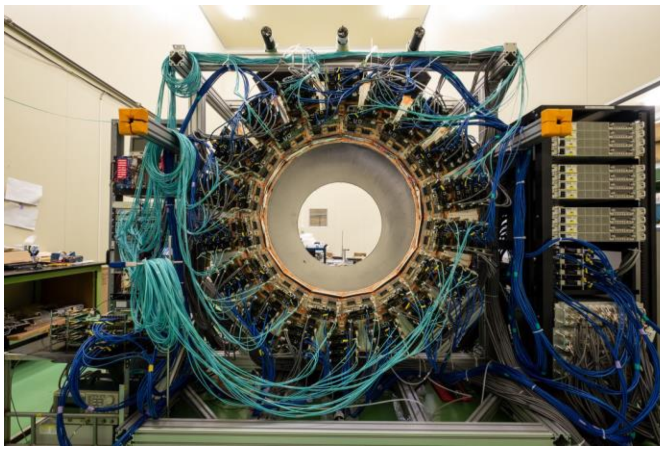
- σ_E/E=4%, $\sigma_{x/y}$=6 mm, σ_t=0.5 ns

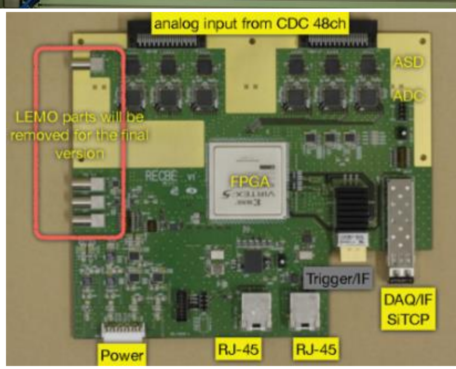
Phase-I support structure completed. ~500 LYSO crystals mounted.



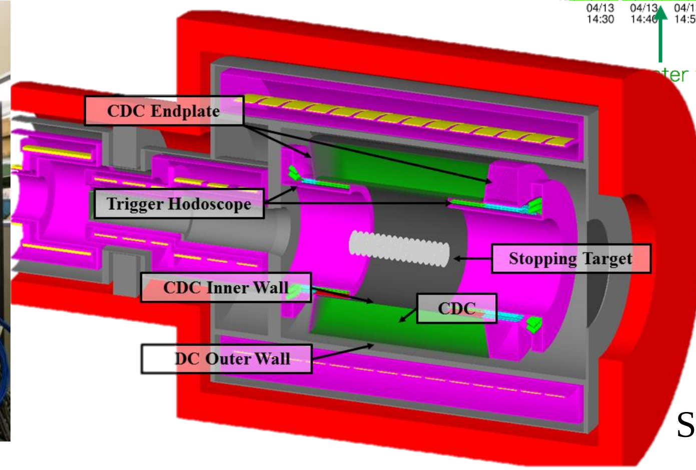
CyDet: CDC

CDC was constructed in 2016 and still working stably.
Moved to J-PARC last year. Now ready to take cosmic ray data for calibration

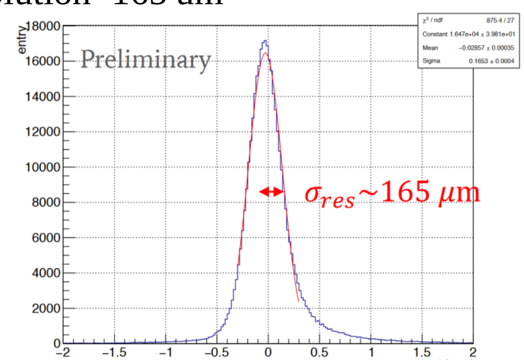


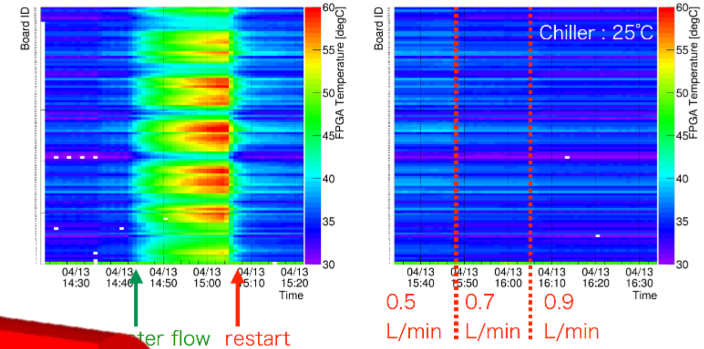


All the 128 boards produced by IHEP group before 2015.
All mounted in 2019.



Filled with He:isobutane=90:10 gas.
Cosmic ray test shows spatial resolution~165 um





Water cooling system designed for the frontend electronics.
Mounted and tested successfully.

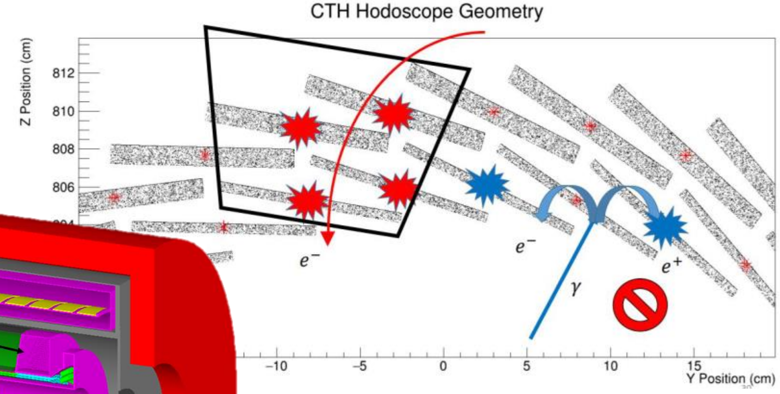
Supporting cradle delivered last month

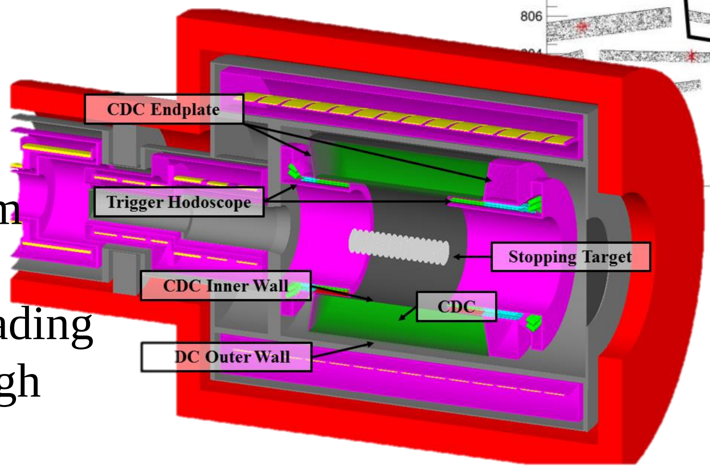
CyDet: CTH

64 scintillators, x2 layers, x2hodoscopes

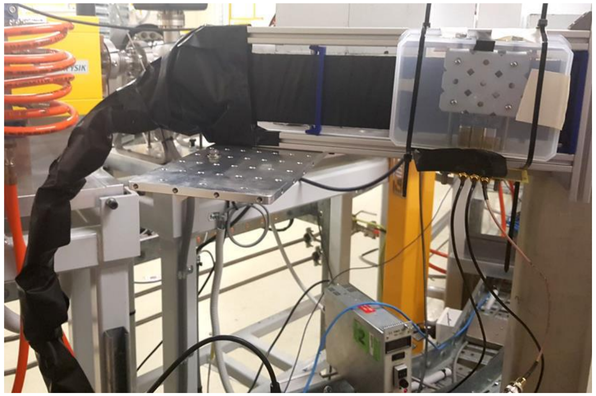
- Stage-I plan. For stage-II, one layer will be replaced by Cherenkov counters.
- Now prototypes are being tested with 100 MeV electron beam
- The readout is SiPM
  - Vulnerable to neutrons.
  - Need extra cooling system to suppress the noise.
  - 5~10 m of optic fibers leading to SiPM outside of the high radiation area

Trigger pattern design

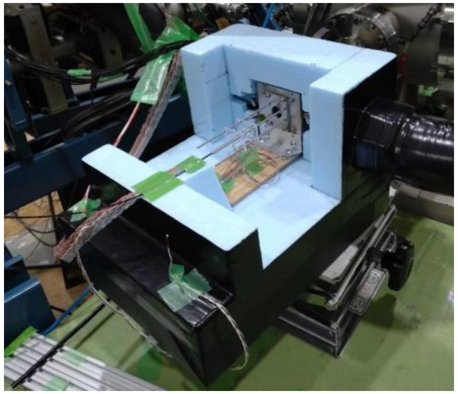




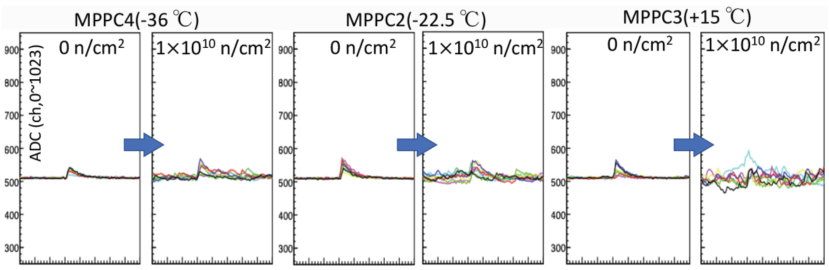
CTH prototype



Readout cooled by N2



cooling and irradiation test last year:
Successfully reduced the noise by cooling

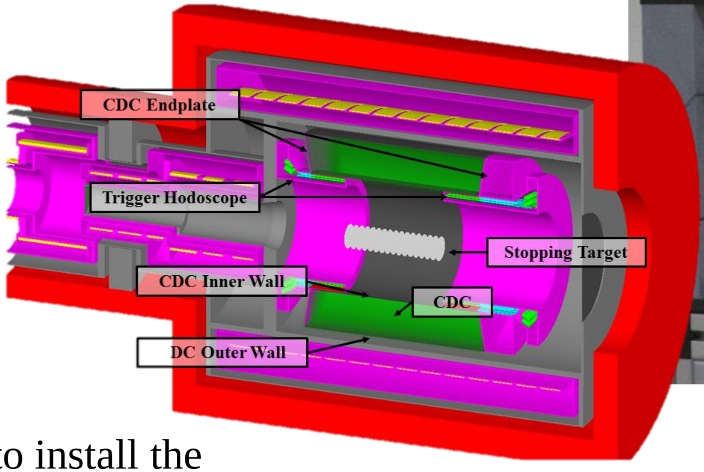


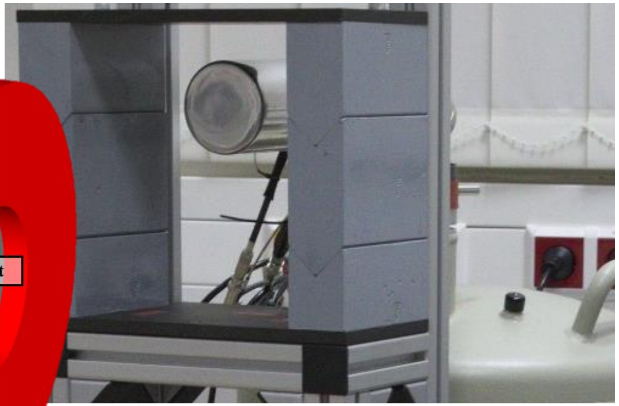
CyDet: stopping target

The stopping target system is under optimization by the Dresden group.

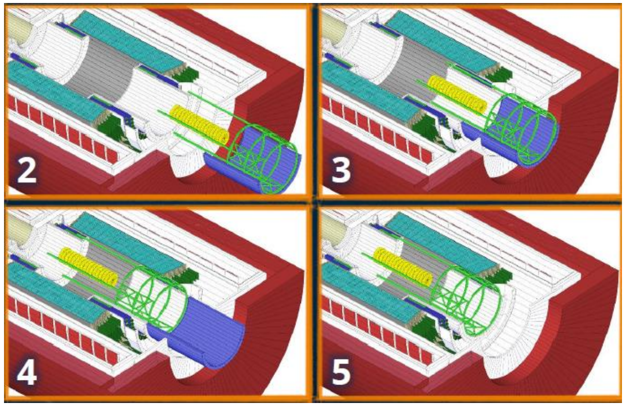
- Number of plates, thickness, etc.
- Prototypes including supporting system produced.

HPGe detector (to calibrate # stopped muons) placed a few meters away from the target. Dresden group is optimizing the shielding design.

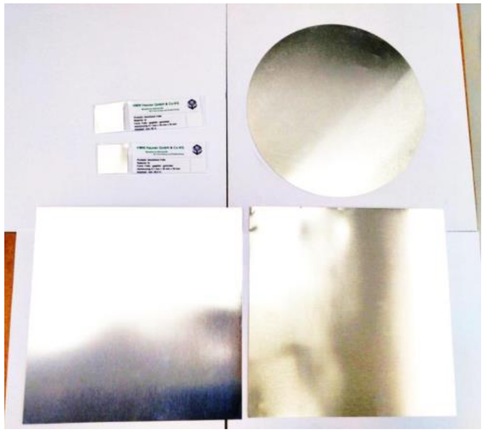




Procedure to install the target system designed.

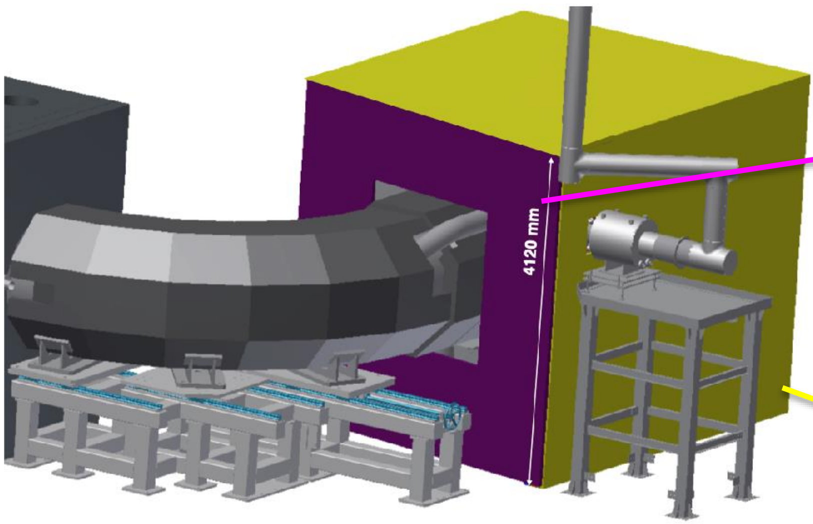


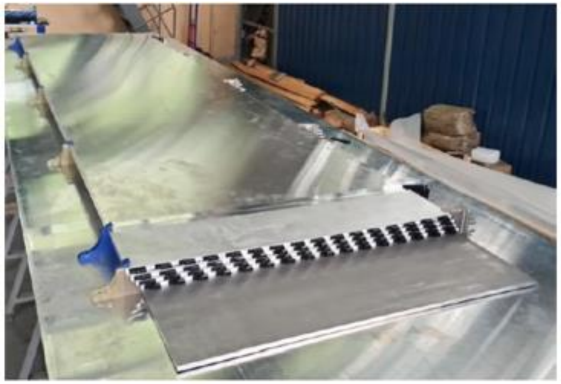
Ongoing tests to choose specific material



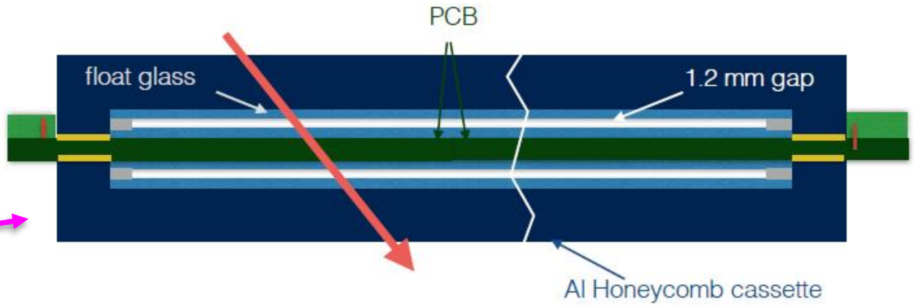
Cosmic ray Veto (CRV)

Design of COMET Phase-I CRV.
Yellow: plastic scintillators (4 layers)
Purple: RPC detector

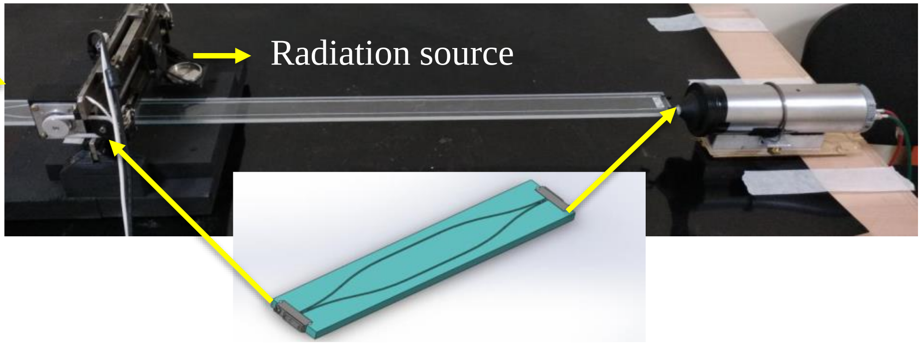




- The RPC design from Clemont.



- Testing with radiation source using SiPM as readout.
  - Preliminary: ¾ coincidence veto ratio ~99.86%

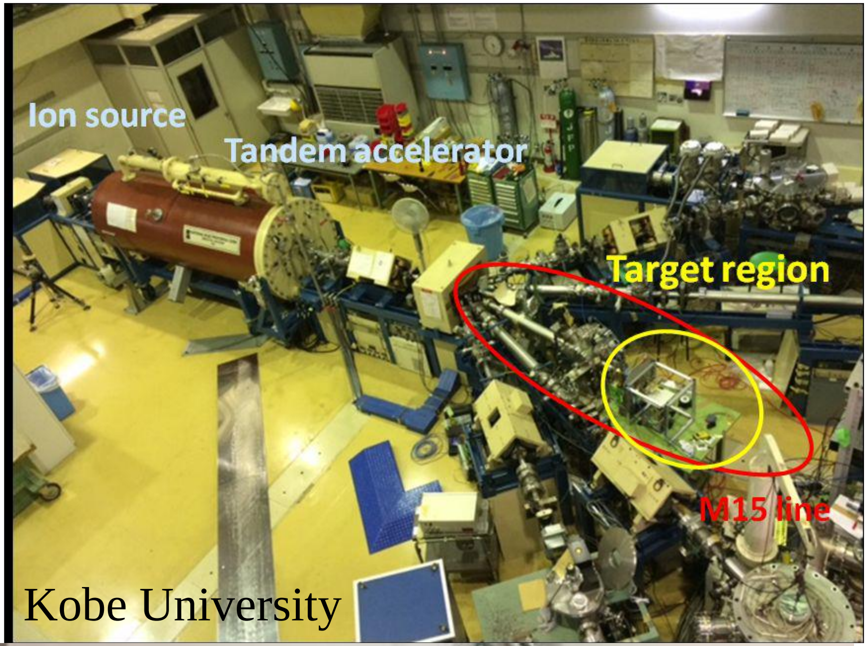


Full size modules produced: 16 strips * 4 layers.

Shipped to J-PARC for further studies.

Radiation Studies

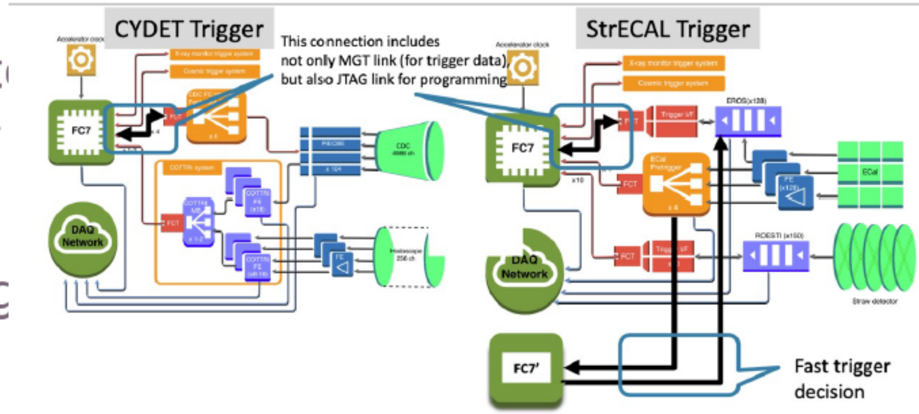
- Neutron Tests
  - Tandem accelerator, Kobe, Univ.
  - ^{9}Be(d,n) reaction with 3 MeV ^{9}Be beam
- Gamma-Ray Tests
  - Radioisotope Research Center, Tokyo Institute of Technology
- Publications:
  - K. Ueno et al., IEEE NSS Conf. Rec. (2016) 8069866
  - Y. Nakazawa et al., NIM A 936 (2019) 351
  - Y. Nakazawa et al. NIM A 955 (2020) 163247



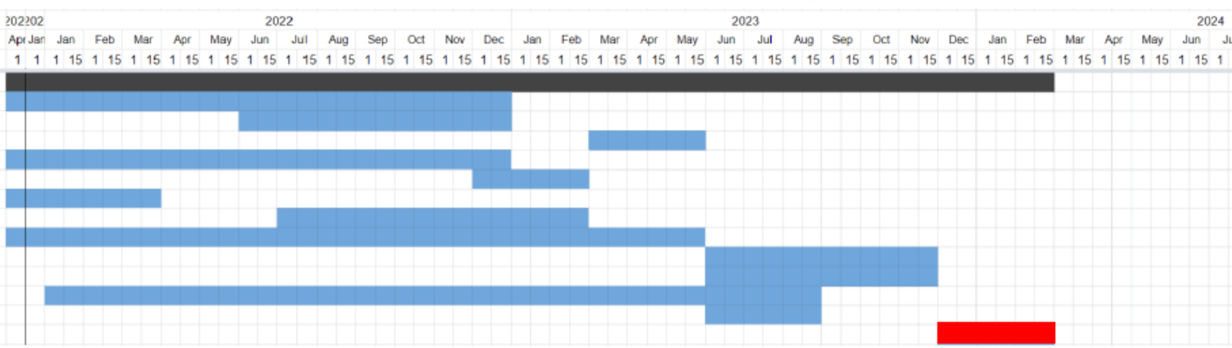
Trigger system for COMET Phase-I

COMET trigger system

- Overall schedule is delayed due t
  international travel restriction by
  COVID-19
- Targeting the trigger conditioninc
  in Dec. 2023-Feb. 2024

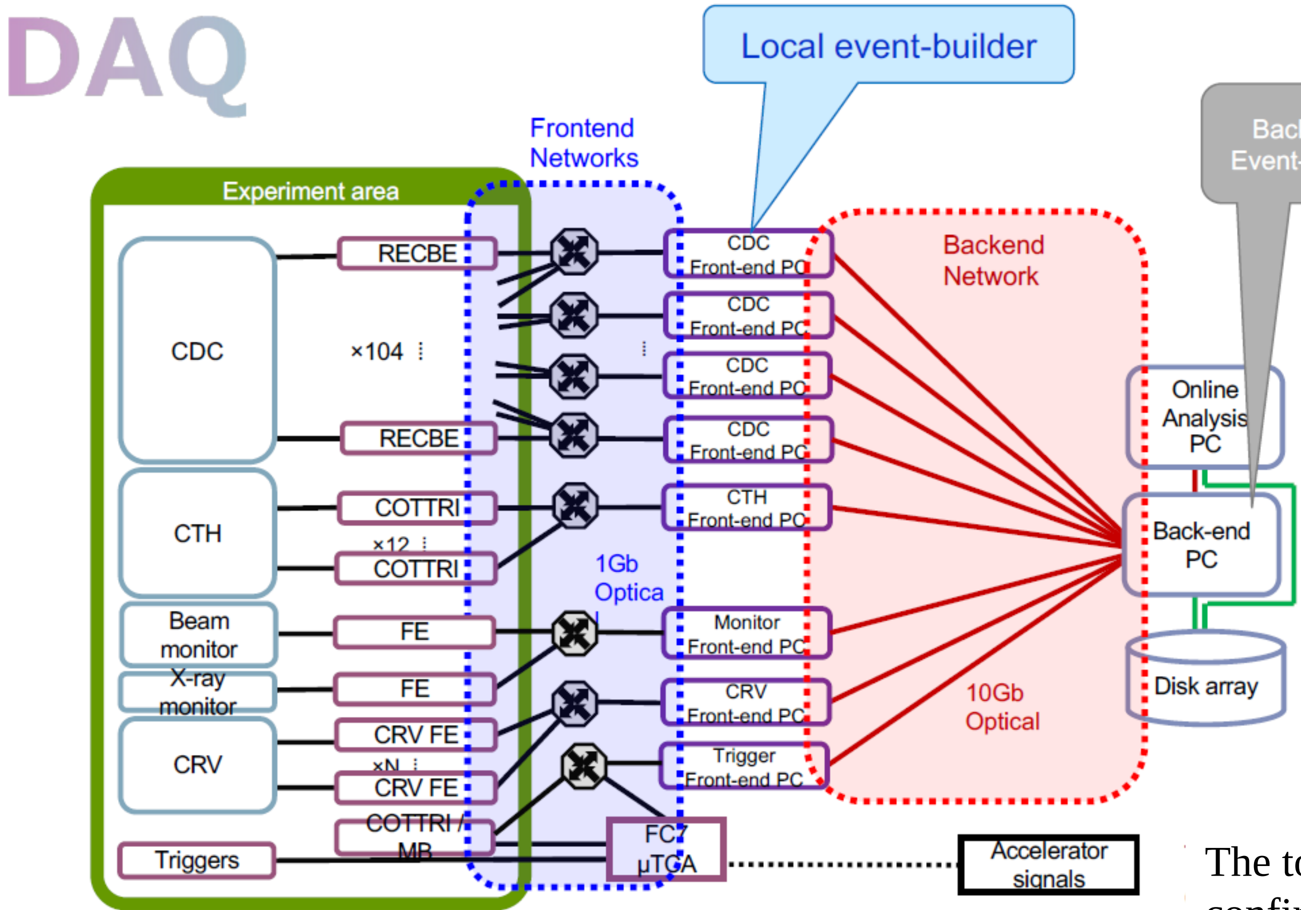


Tas	Task	Assigned to	Process	Start	End	Cost
-5	Trigger	SKKU		04/01/2020	02/28/2024	
5	Central system R&D and Preparation	SKKU		04/01/2020	12/31/2022	
5	Straw chamber feedthrough production	SKKU		06/01/2022	12/31/2022	
5	FCT for acc. timing measurement	SKKU		03/01/2023	05/31/2023	
5	COTTRI HW production and test	Monash		04/01/2020	12/31/2022	
5	COTTRI - Central system chain test	SKKU/Monash/KEK		12/01/2022	02/28/2023	
5	Pretrigger HW preparation	BINP		04/01/2020	03/31/2022	
5	Pretrigger - Central system chain test	SKKU/BINP/KEK		07/01/2022	02/28/2023	
5	CRV Trigger HW production	CRV G		04/01/2020	05/31/2023	
5	CRV Trigger logic development	SKKU		06/01/2023	11/30/2023	
5	MBM trigger logic development	SKKU		06/01/2023	11/30/2023	
5	TRG Cable Installation at COMET site	Trigger G/KEK		01/01/2022	08/30/2023	
5	TRG Installation at COMET site	Trigger G/KEK		06/01/2023	08/30/2023	
5	TRG Conditioning	Trigger G		12/01/2023	02/28/2024	



Dec. 2023-Feb. 2024

DAQ for COMET Phase-I



The total throughput of 1 GB/s confirmed

Monte Carlo study of COMET Phase-I

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was published in 2021.
  - Sensitivity:
    - Total acceptance of signal is 0.041
    - Can reach 3×10^{-15} SES in 150 days, 90% C.L. u.l. 7×10^{-15}
  - Background:
    - With 99.99% CRV veto ratio, total expected background is 0.032
  - Trigger rate:
    - Average trigger rate ~10kHz (after trigger with drift chamber hits)

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 (ε_{mom})	0.93
Timing window ($\varepsilon_{\text{time}}$)	0.3
Total	0.041

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.

Progress of Theoretical and Experimental Physics, 2020, 2020(3)

Other Physics Topics on COMET

- $\mu^- N_Z \rightarrow e^+ N_{Z-1}$: Lepton number violation (LNV)
  - Current limits: $\mu^-\ Ti \rightarrow e^+\ Ca(gs) \leq 1.7\ \times\ 10^{-12}$
    $\mu^-\ Ti \rightarrow e^+\ Ca(ex) \leq 3.6\ \times\ 10^{-12}$
  - Can improve with a proper target

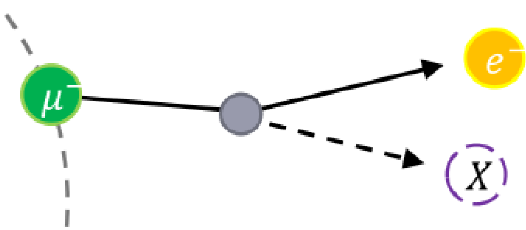
Phys. Lett. B422 (1998)

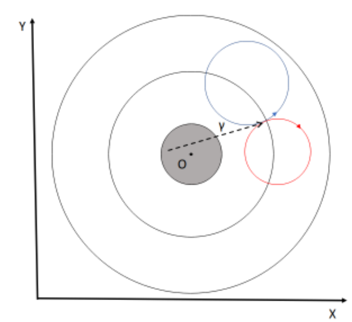
Phys. Lett. B764 (2017)
Phys. Rev. D96 (2017)

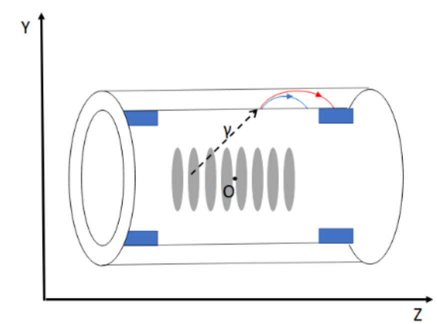
Lee, MyeongJae(for COMET), and Michael MacKenzie(for Mu2e) Universe 8, no. 4: 227

- $\mu^- \rightarrow e^- X$: X can be a new light boson, axion, etc.
  - feasibility being studied in COMET

Chinese Physics C. Vol. 47 No. 1 (2023) 013108







- Radiative muon capture process
  - Ph.D thesis by Dorian

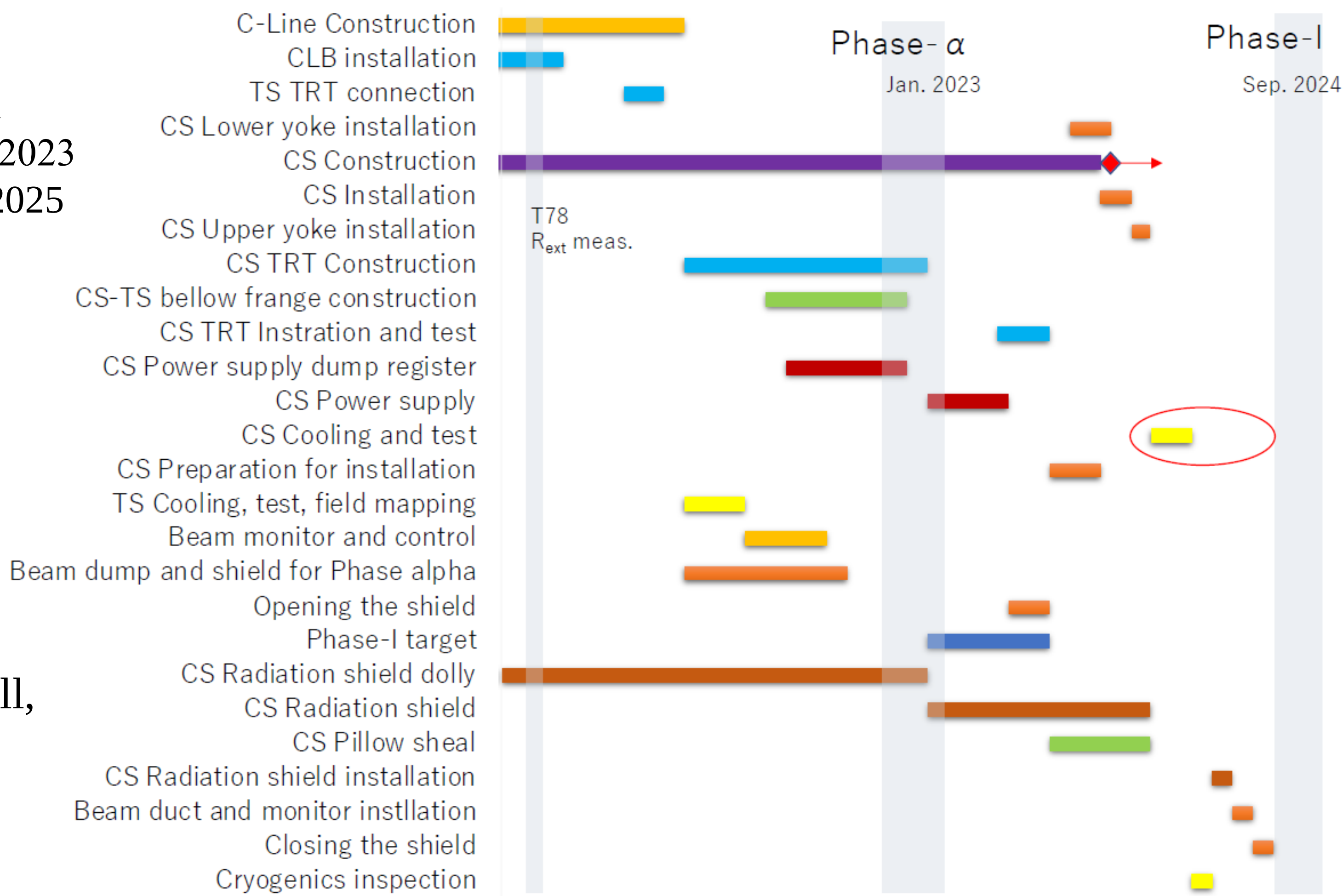
$$\mu^- + N(Z) \rightarrow N'(Z-1) + \nu_\mu + \gamma;$$

Timeline for COMET Phase-I

Schedule of Phase-α and Phase-I

- ✓ 8 GeV test and R_{ext} measurement in 2021
- ✓ Phase-α Eng. Run in 2023
- ✓ Phase-I Phy. Run in 2025

- With the recent incident in CS, it's possible that the beam time will be delayed by a few months.
- Before the CS is ready, after the DS is ready in 2024 fall, cosmic ray measurement will be carried out.

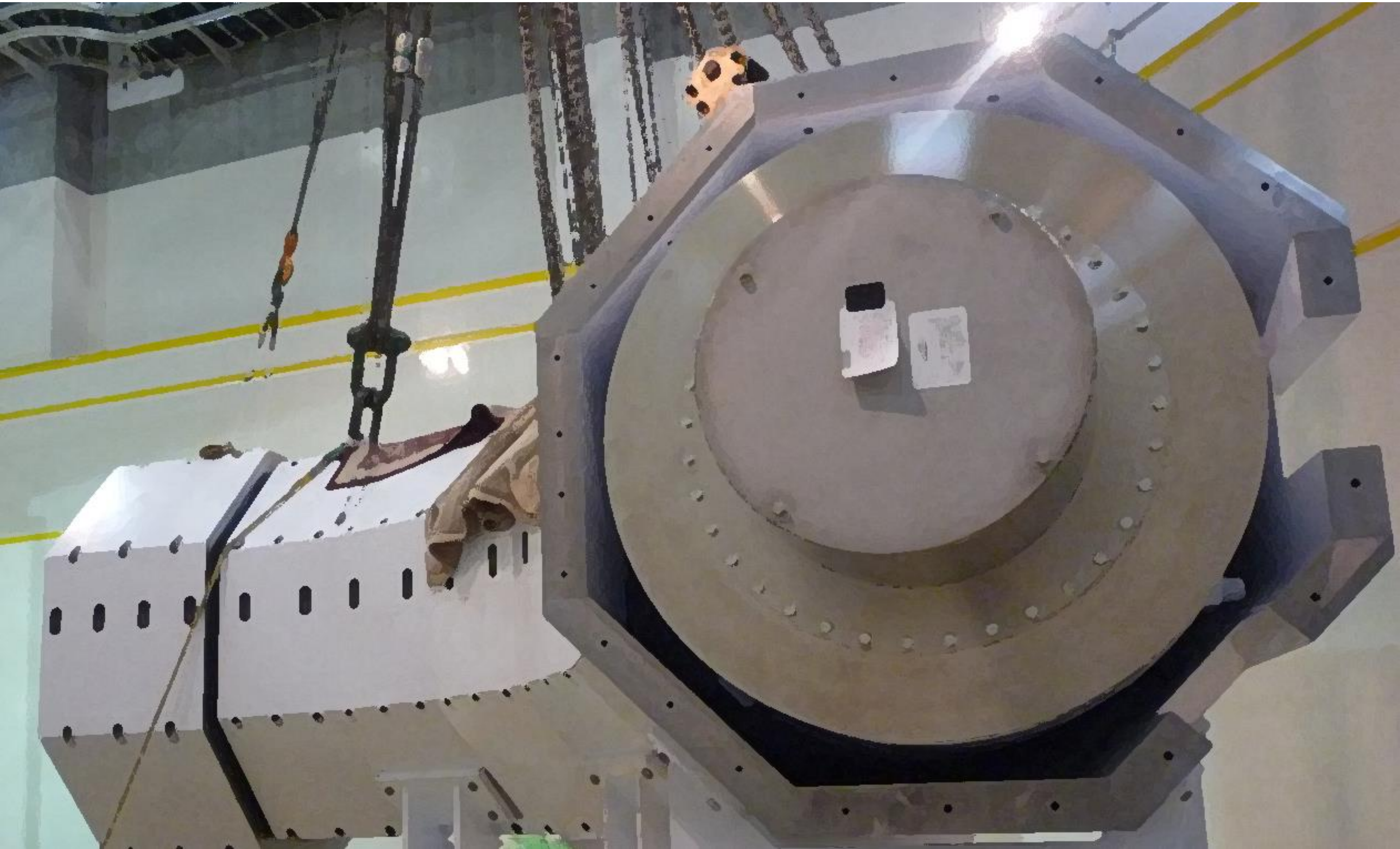


COMET Phase-II optimized

- The COMET Phase-II design was under complete re-optimization by a Ph.D. candidate Weichao Yao.
- COMET Phase-II beam power (56 kW) is stronger than that of the Mu2e.
- 90% C.L. upper limit improved to 7×10^{-18}
  - By redesigning the production target dimension, the muon beamline, and the stopping target system, the DIO suppression solenoid, and by increasing the running time
  - Similar to Mu2e-II!
- Assuming COMET Phase-I can be finished in 2027.
- After 3 years of construction, COMET Phase-II may start from ~2030.

	Phase-I	Phase-II	(Phase-II)+
proton beam	8 GeV, 3.2 kW	8 GeV, 56 kW	8 GeV, 56 kW
proton target	graphite	tungsten	tungsten
transport	90° bend	180° bend	180° bend
muons stop	1.2×10^{9}/s	1×10^{18}	2×10^{11}
run time	150 days	200 days	300 days
detector	CyDet	StrECAL	StrECAL
90% CL	$< 7 \times 10^{-15}$	$< 4.6 \times 10^{-17}$	$< 7 \times 10^{-18}$
backgrounds	0.03 events	0.32 events	0.6 events

Summary



Summary

- COMET is going to search for coherent muon to electron process.
  - Aims at single event sensitivity (S.E.S) = 2.6×10^{-17} (4 orders of magnitude improvement) with 1 year beam time using 56 kW 8 GeV proton beam.
  - With the same beam power, **10** times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is about to be finalized.
- COMET will be carried out in two phases and Phase-I is under construction.
  - Aims at S.E.S = 3×10^{-15} (2 orders of magnitude improvement) with 150 days beam time using 3.2 kW 8 GeV proton beam.
  - Will directly measure the muon beam.
- COMET Phase-I is expecting its beamtime in 2024~2025
- COMET Phase-II can start construction from 2027 and start data taking from 2030.

Thank You!