The COMET experiment:
A search for muon-to-electron conversion at J-PARC

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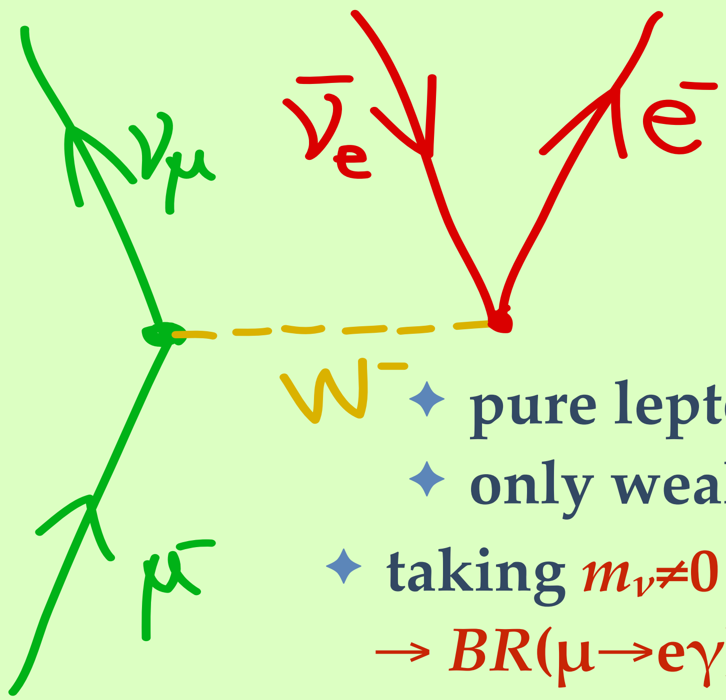
on behalf of the COMET collaboration

Contents

Search for Charged Lepton Flavour Violation via μ-decay

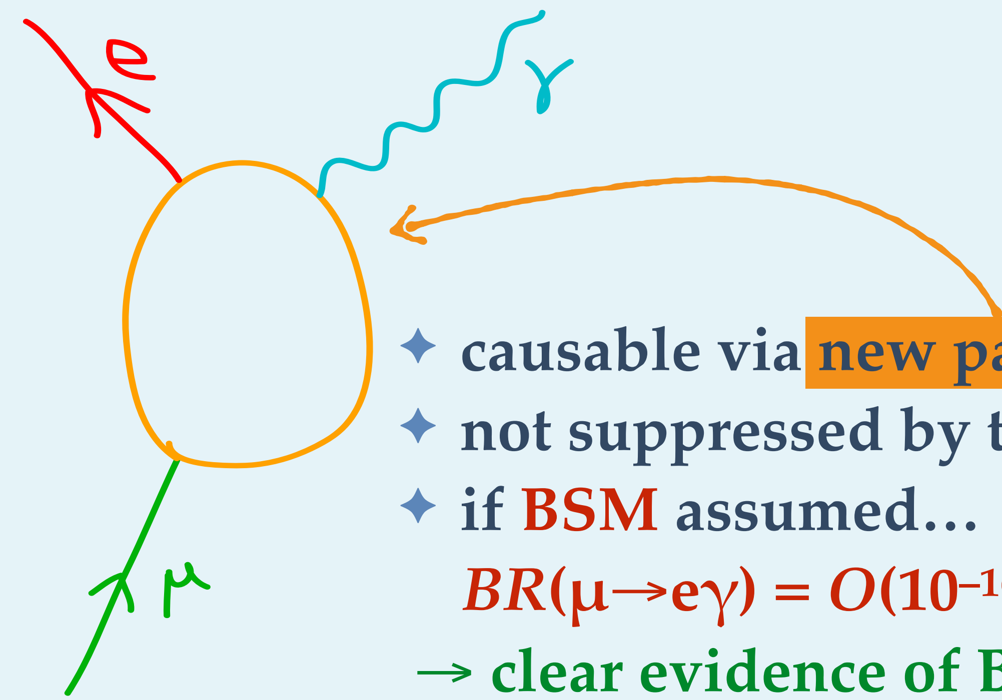
- **Muon is Best Probe to search for CLFV; *eg*. $\mu^+ \to e^+\gamma$, $\mu^- N \to e^- N$, $\mu^+ \to e^+e^+e^-$**

μ decay in SM



- pure leptonic
- only weak interaction
- taking $m_\nu \neq 0$ into account
  → $BR(\mu \to e\gamma) < O(10^{-54})$

μ LFV in BSM

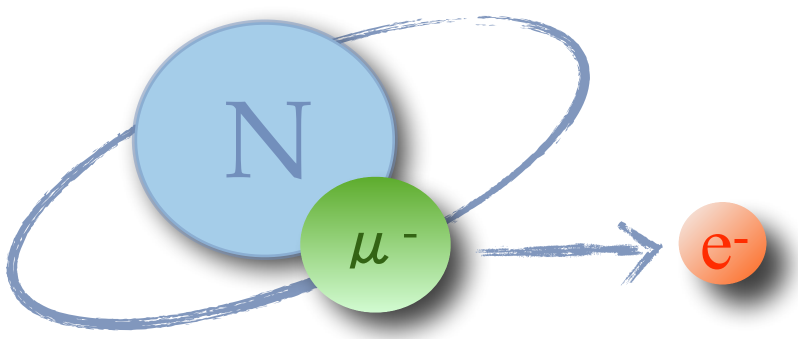


- causable via new particle
- not suppressed by tiny m_ν
- if BSM assumed…
  $BR(\mu \to e\gamma) = O(10^{-16}\text{-}10^{-13})$
  → clear evidence of BSM

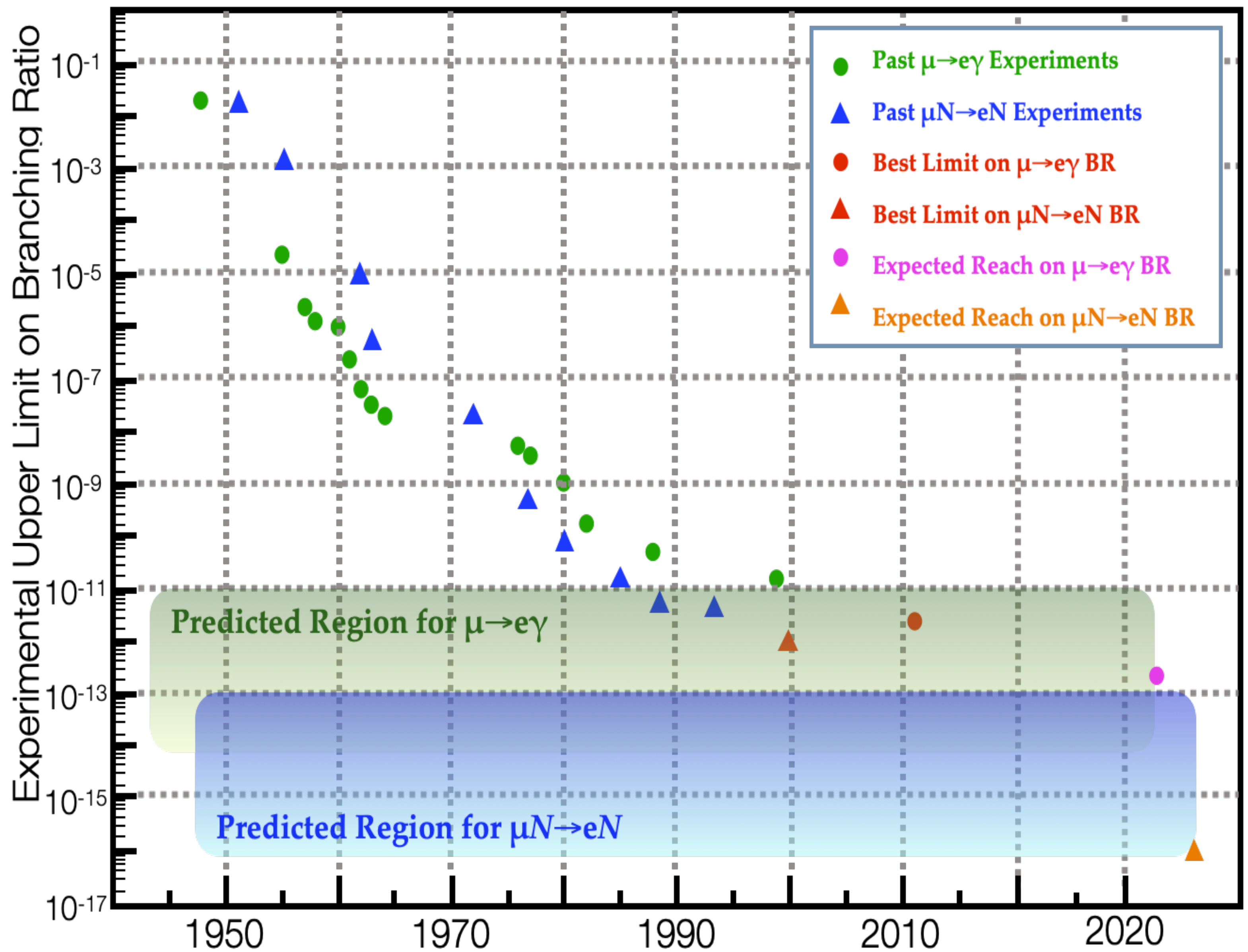
- **Try to Explore New Physics via "*Charged Lepton Flavour Violation*"**
- **Among "Quark", "Neutrino" = Known as Flavour violated**
- **"Charged Lepton Flavour Violation (cLFV)" = Never Observed so far**
  - Very sensitive to the TeV-scale new physics beyond Standard Model
    → **Complementary** and **Competitive** to the **Energy Frontier (*eg*. LHC)**

$\mu^- N \to e^- N$ Search

- "Muon-to-Electron Conversion in Muonic Atom ($\mu^- N \to e^- N$)"
  - Charged LFV, So-called "μ-e Conversion"
  - One of the most prominent process of muon LFV



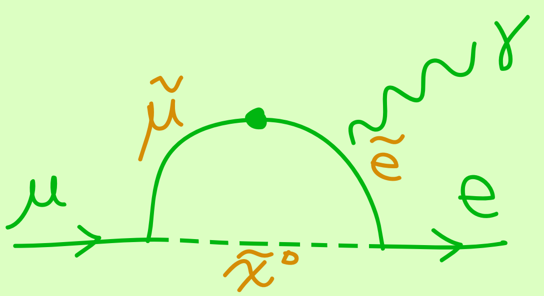
- "Signal"
  - $E_e = m_\mu - B_\mu - E_{recoil}$
    ~105 MeV (muonic Al)
- "Background"
  - Beam-related
  - Normal muon decay in Orbit (DIO)
  - Cosmic-ray induced

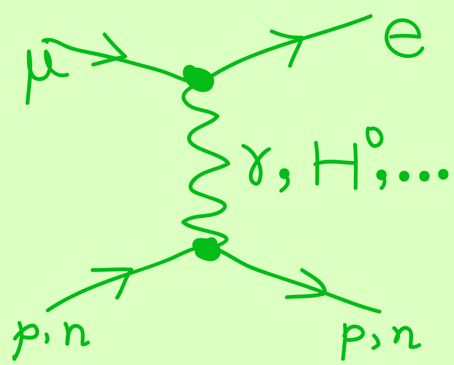


"$\mu^- N \to e^- N$" *vs.* "$\mu^+ \to e^+ \gamma$"

- **Very similar, *twin* processes**
- **But, big differences from points-of-view of *Physics* and *Experiment***
- **Searching for both processes is important**

Differences in *Physics*

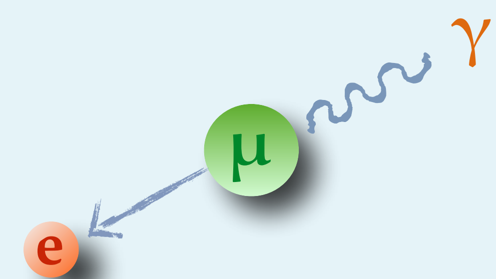


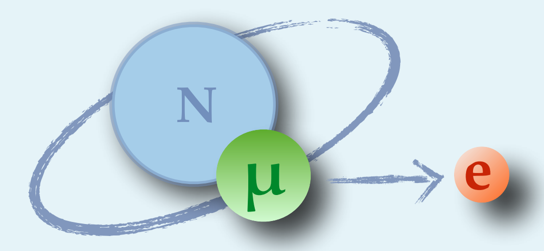


- sensitivity for *photonic* process and *non-photonic* process is different
- $\mu \to e\gamma$: photonic👍 non-photonic👎
- μ-e conv : photonic👍 non-photonic👍

→ Very powerful tool to probe properties of new physics when the signal is discovered.

Differences in *Experiment*

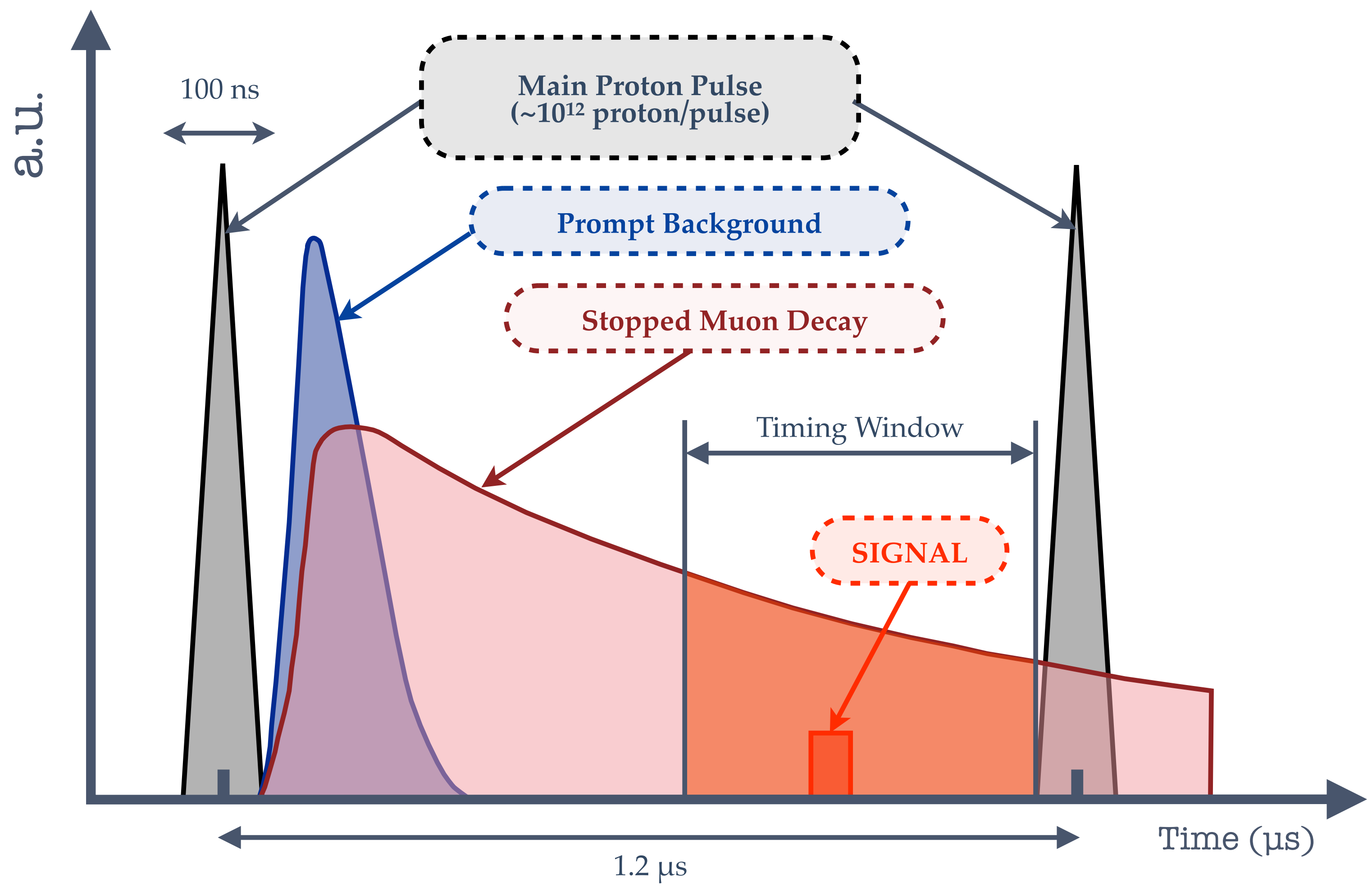




$\mu \to e\gamma$ Search	$\mu N \to e N$ Search
Signal = Coincidence	Signal = Mono-E e^-
⬇️	⬇️
Dominant B.G. is **Accidental Overlap**	Dominant B.G. is **Beam related**
Challenge = Detector	Challenge = Beam
DC beam ! (PSI *et.al.*)	**Pulse beam !** (J-PARC *et.al.*)

Beam-related Background to Search for μ-e Conv.

- **Dominant Background**
  - Beam-related prompt Background, mainly caused by pion decays
  - Muonic atom (of Al) has a lifetime of ~1μsec
  - Delayed DAQ-window right before the next proton bunch allows for BG-free Search
- **Extinction is ESSENTIAL !**



$$\textbf{Extinction} = \frac{\textbf{\# of leaked protons in between bunches}}{\textbf{\# of filled protons in main bunches}}$$

Extinction should be $<10^{-10}$ at least to achieve the COMET Goal

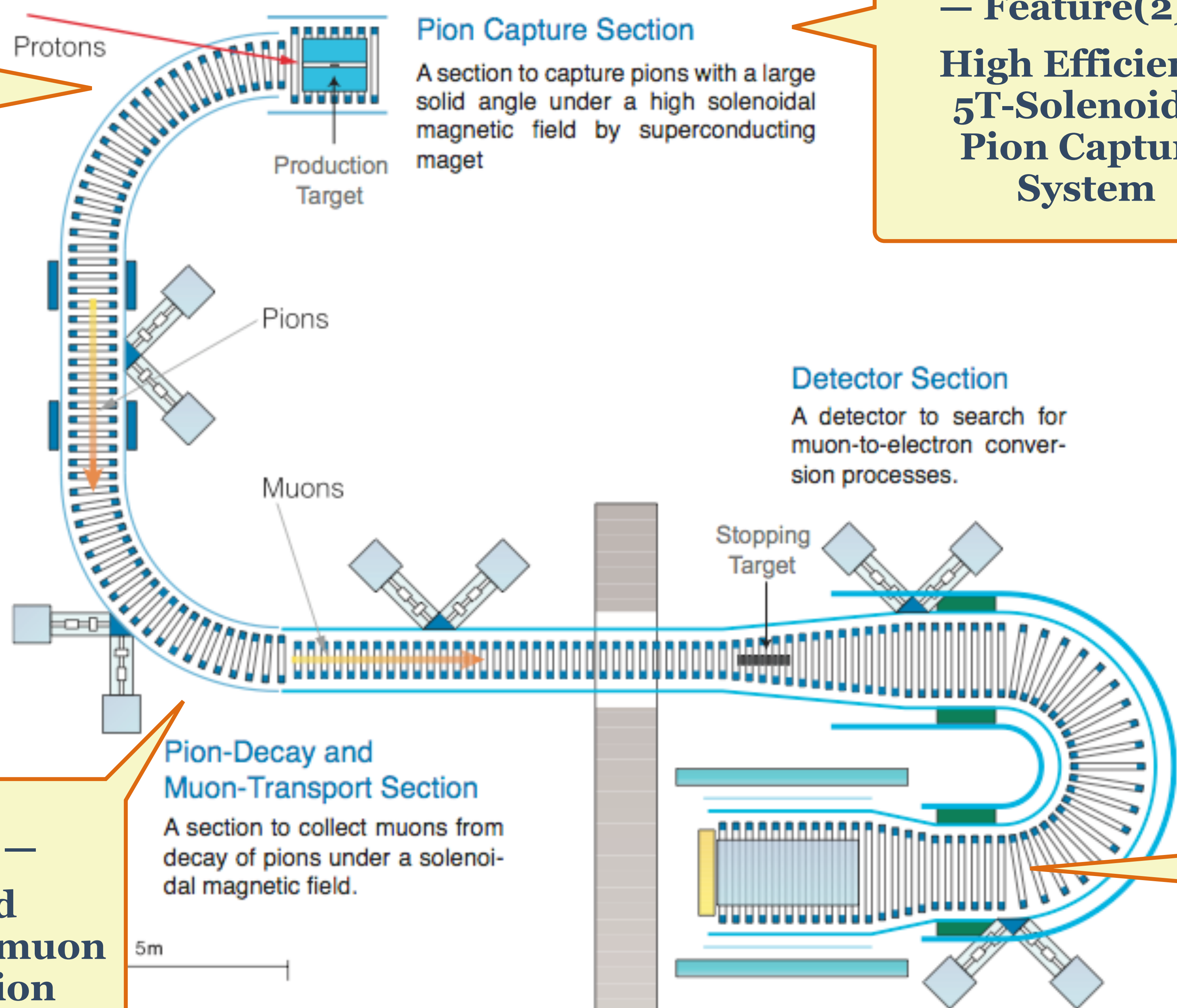
(Single Event Sensitivity : 10^{-17})

The COMET Experiment

- **Enabled by "Four Features" → Aim to achieve target sensitivity of $O(10^{-17})$**

— Feature(1) —
High Intensity Pulsed Proton Beam by J-PARC

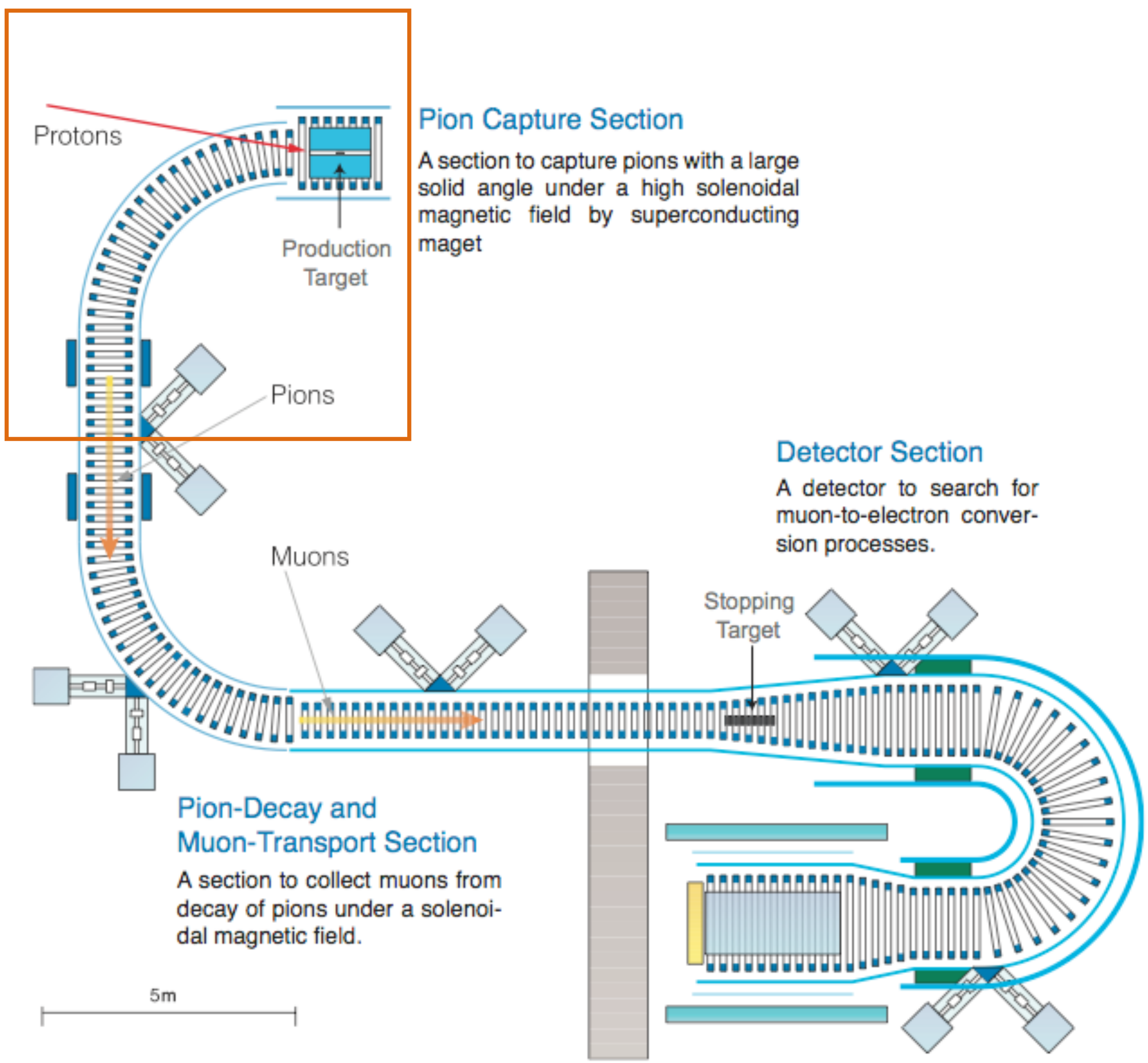
— Feature(2) —
High Efficiency 5T-Solenoidal Pion Capture System



— Feature(3) —
Long/Curved Solenoidal pion/muon transport section

— Feature(4) —
High resolution, vacuum compatible electron spectrometer

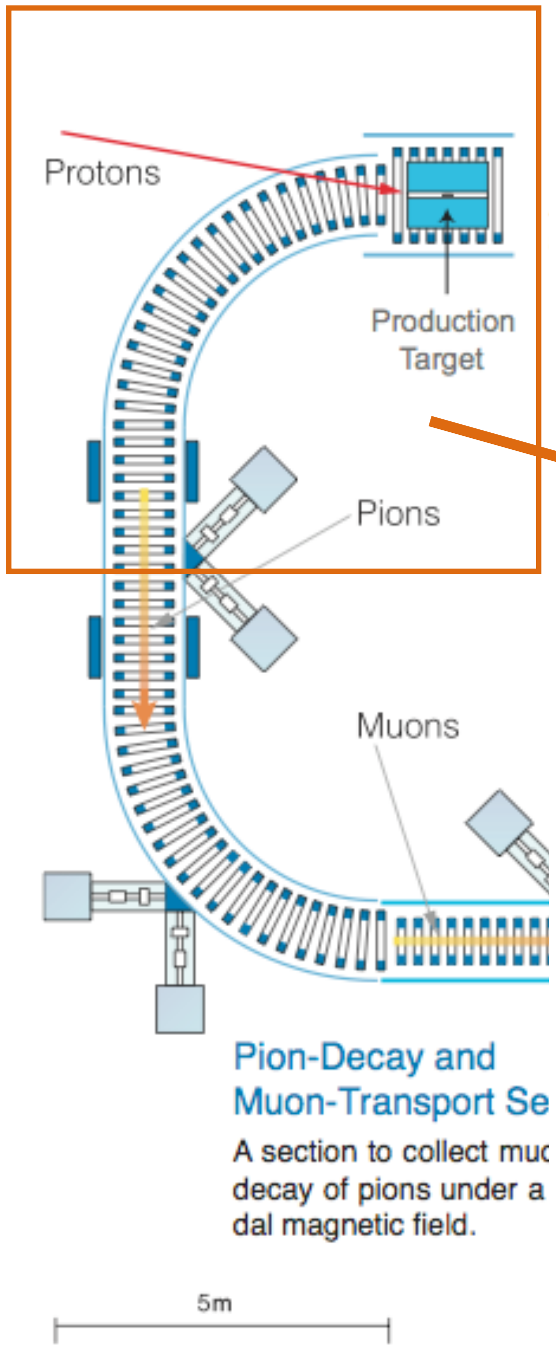
Two-Staged Approach

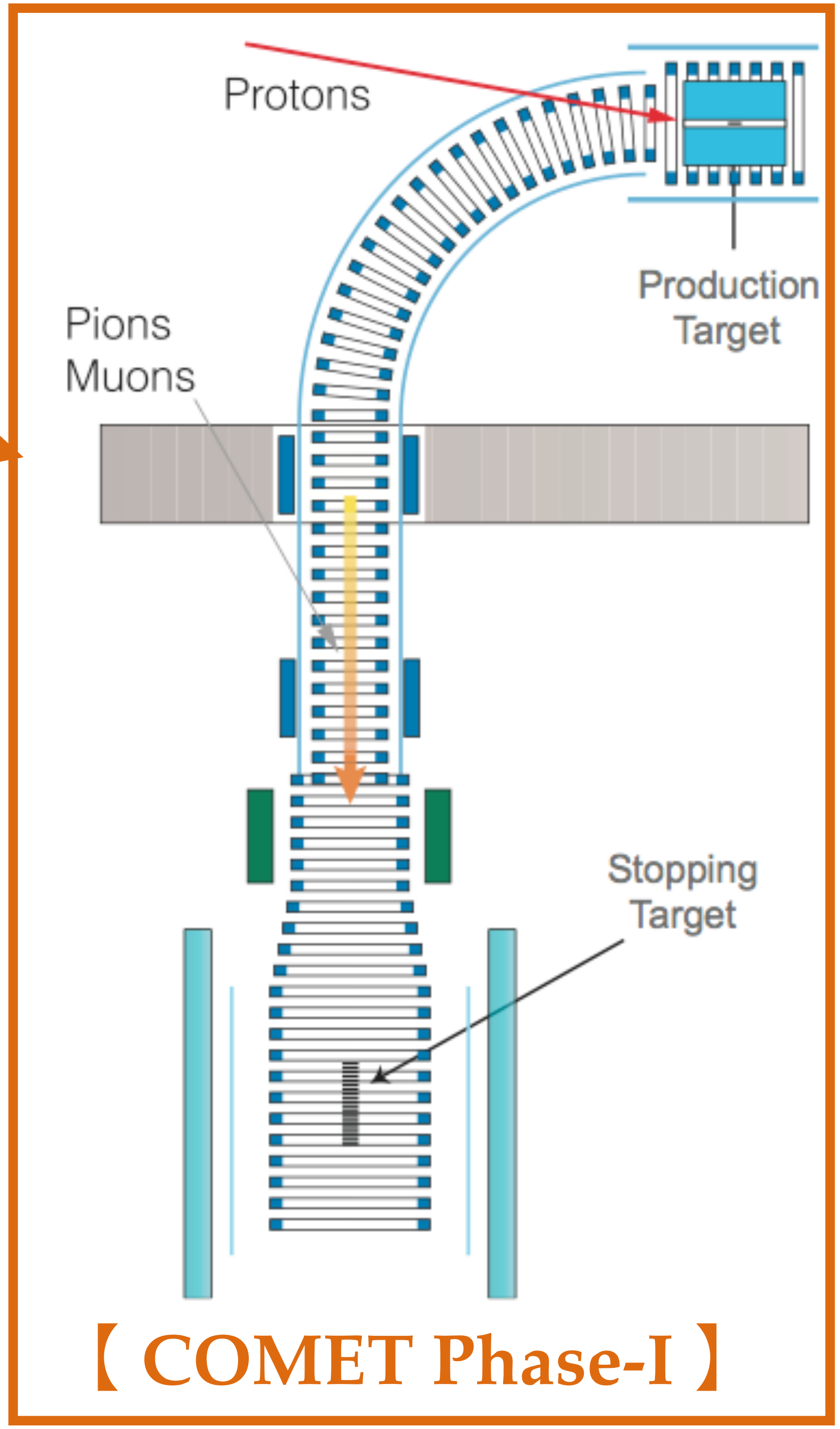


- **COMET Phase-I**
  - Construct up to first 90° bend and place detector.
  - Perform direct beam measurement
    - No backward σ_π data so far
    - No real BG data so far
  - Perform μ-e Search with an intermediate sensitivity ($O(10^{-15})$)

- **COMET Phase-II**
  - Complete all transport
  - Perform μ-e Search with a full sensitivity ($O(10^{-17})$)

Two-Staged Approach





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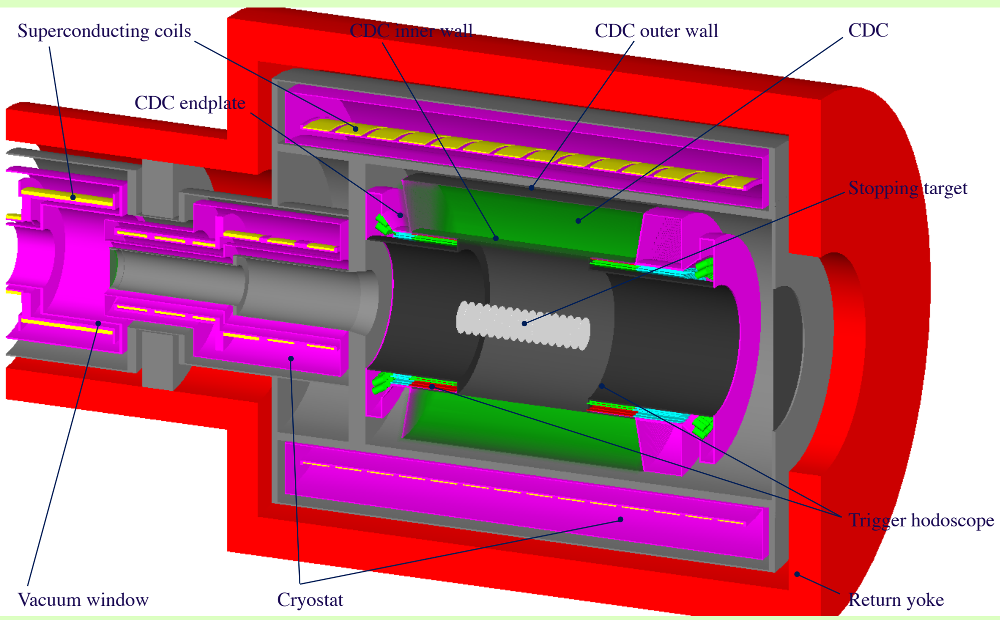
  - Complete all transport
  - Perform μ-e Search with a full sensitivity ($O(10^{-17})$)

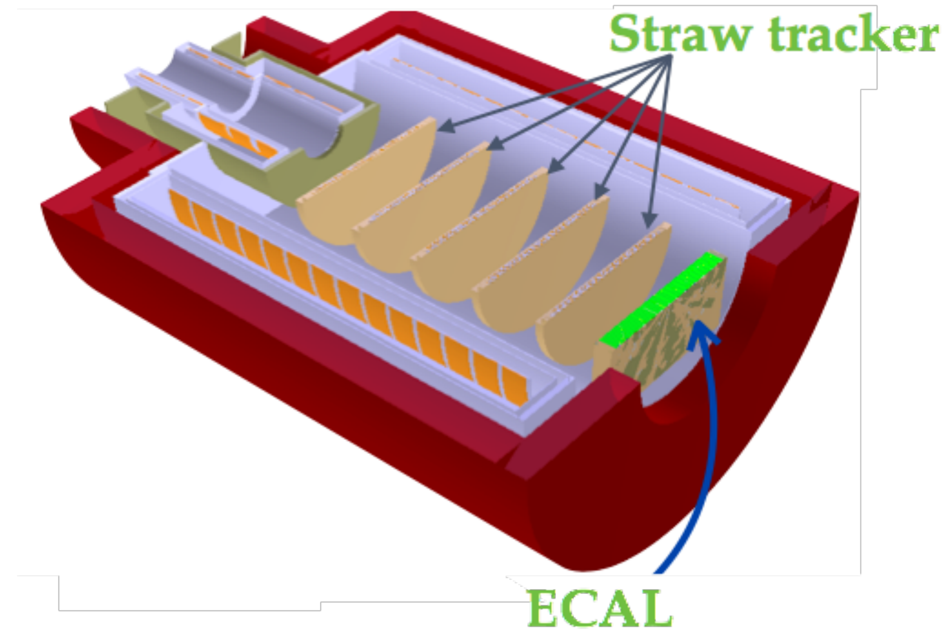
Detectors for Phase-I

For μ-e Conversion Search



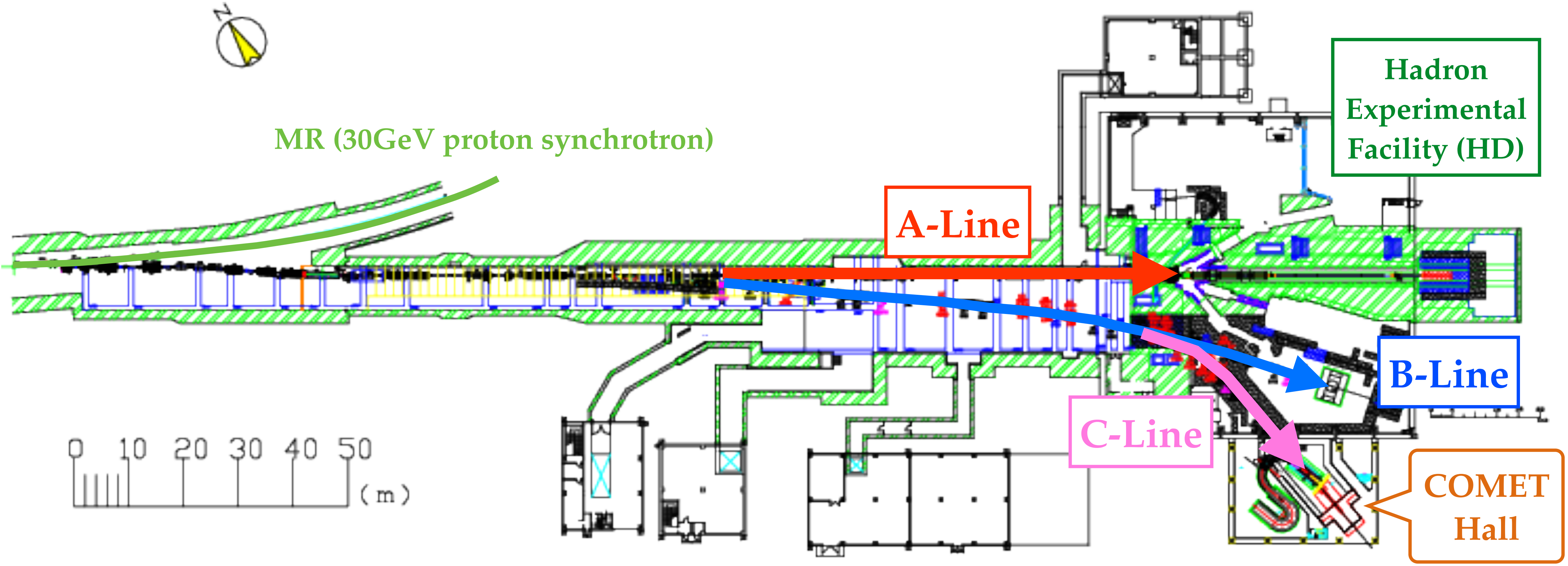
- "CyDet" = Cylindrical Detector System
- For Phase-I, centre part of beam is dominated by BG, *i.e.* Cylindrical Drift Chamber and Cylindrical Trigger Hodoscope is employed to search for μ-e conversion.
- He-iC_4H_{10} gas-mixture to reduce material budget, Hollow cylinder design to have a BG tolerance

For Beam Measurement



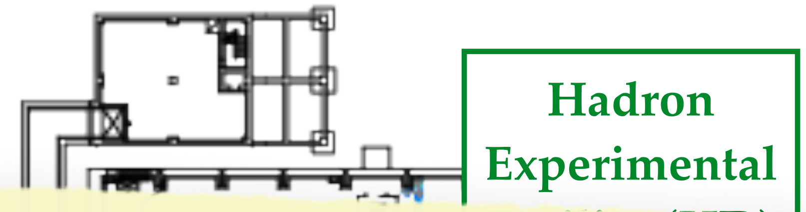
- "StrECAL" = Straw tracker and ECAL
- To measure all delivered beam incl BG, vacuum-compatible tracker and calorimeter is employed
- Straw = Planer/Low-mass, LYSO crystal ECAL = High resolution / High density
- Same concept as Phase-II detector = Prototype of Phase-II Final Detector

Current Status (1) — Facility Construction —

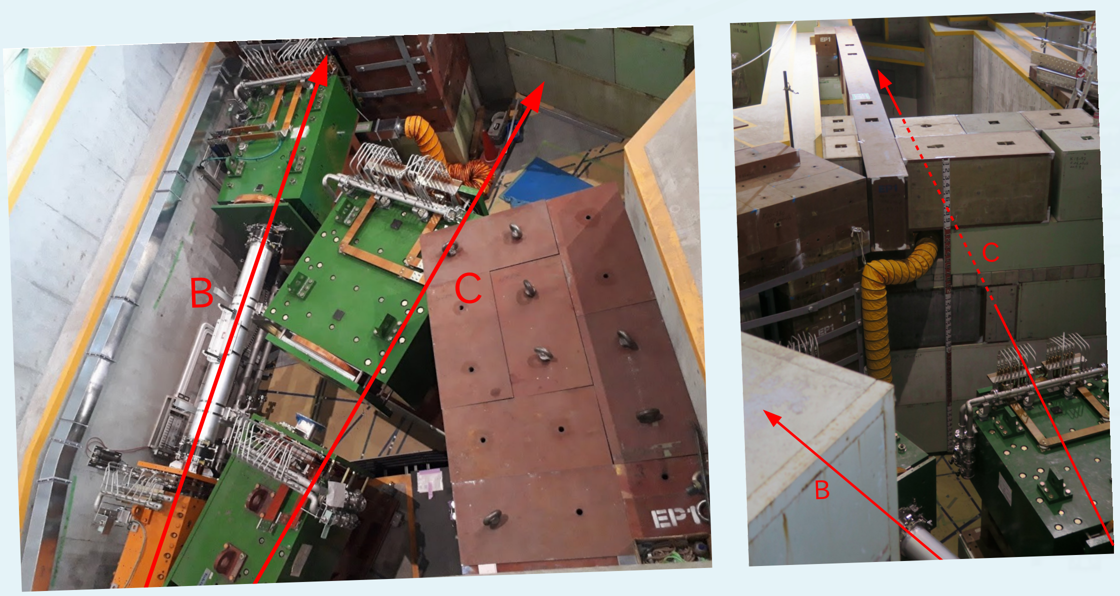


- Dedicated proton beam line is under construction.
  - Three proton beam lines in Hadron Experimental Facility. **A-Line** is primary and in-operation. **B-Line** just completed and started operation in June 2020. **C-Line**, dedicated for COMET, is under construction and expected to be completed in 2021.
- Inside COMET hall, pion/muon transport system is under construction.
  - Transport solenoid is already completed. Other components, pion capture solenoid, detector solenoid *etc*., are under construction.

Current Status (1) — Facility Construction —

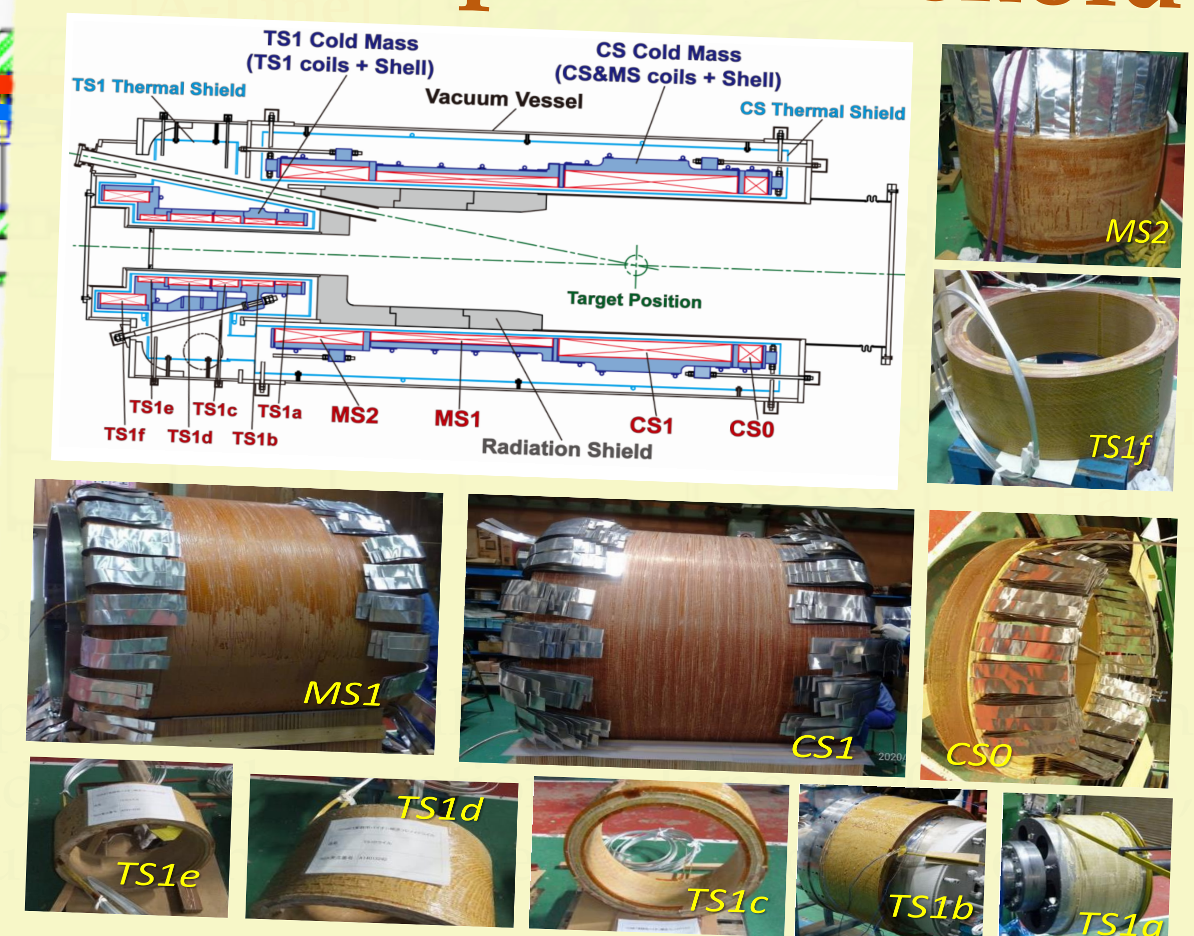


Proton Beam Line



B-Line, completed and in-operation. C-Line, under construction and will be completed in 2021. First beam will be delivered to COMET hall in 2022.

Pion Capture Solenoid

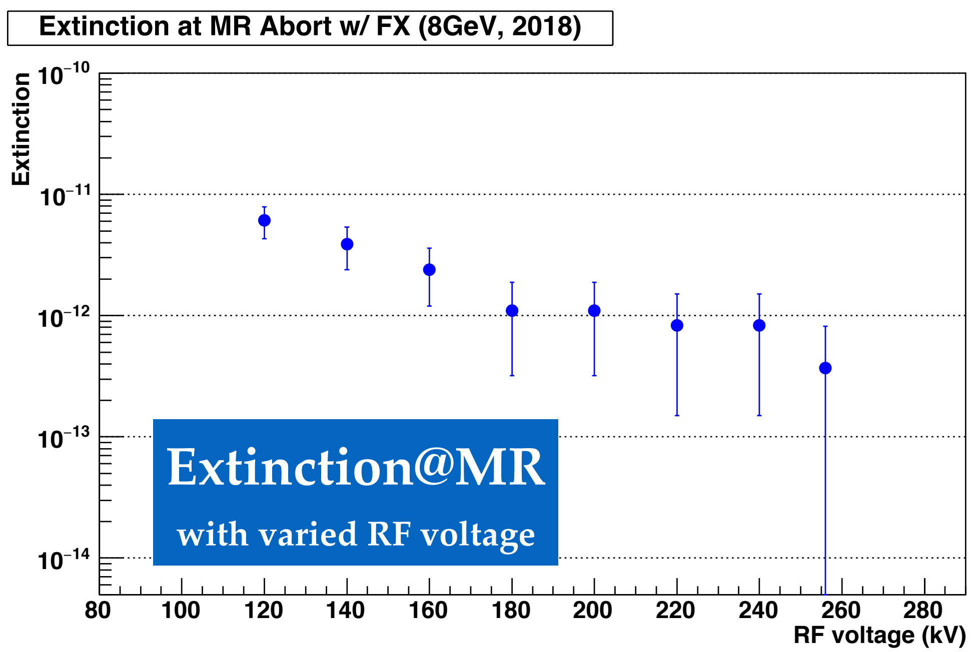


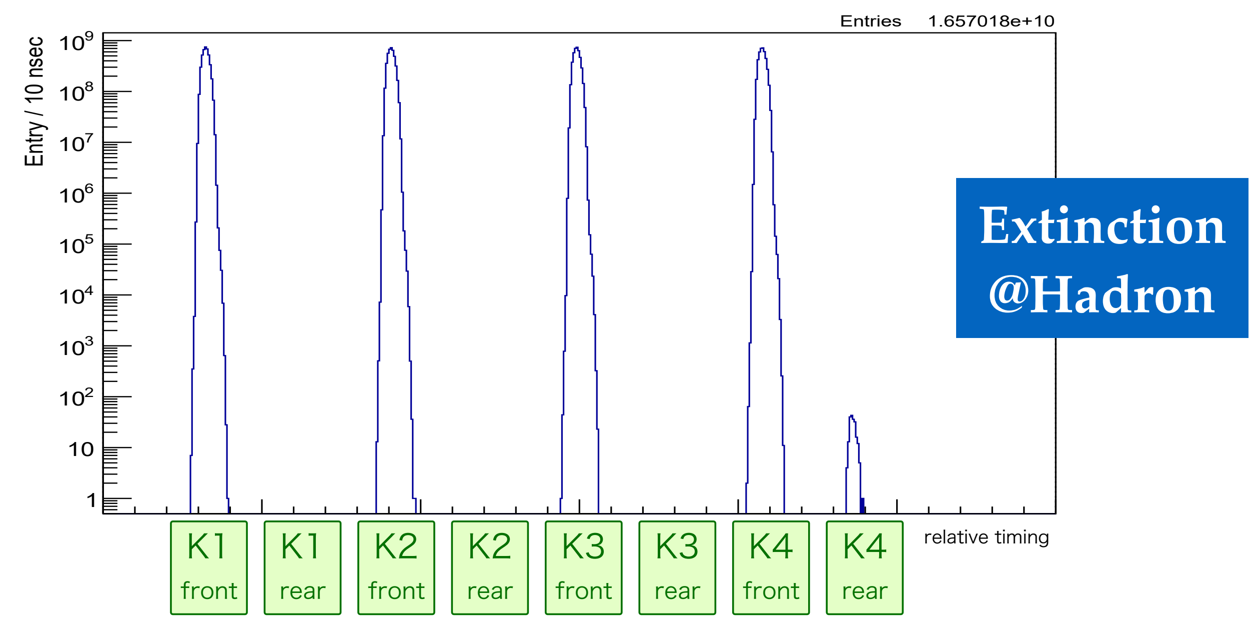
All coils ready. Construction for all parts started. Will be completed in 2022.

- Transport solenoid is already completed. Other … solenoid, detector solenoid *etc.*, are under construction.

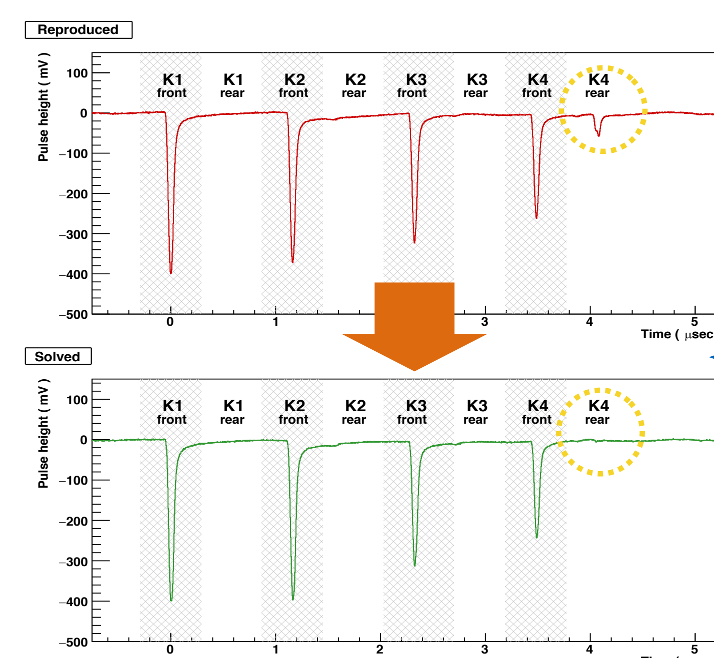
Current Status (2) — Accelerator Development —

- **Dedicated 8 GeV Operation Test was conducted in Jan-Feb 2018.**
  - Operation chain; injection / acceleration / extraction, successfully established.
  - Good bunched slow extraction efficiency of 97% , achieved





- **Extinction development** was also successfully conducted at Main Ring Proton Synchrotron and Secondary Beam Line in Hadron Experimental Facility.
- **Excellent extinction ($O(10^{-12})$-$O(10^{-11})$)** in MR was confirmed. But, Small leaks observed in secondary beam (equivalent to $1\text{x}10^{-10}$ extinction)

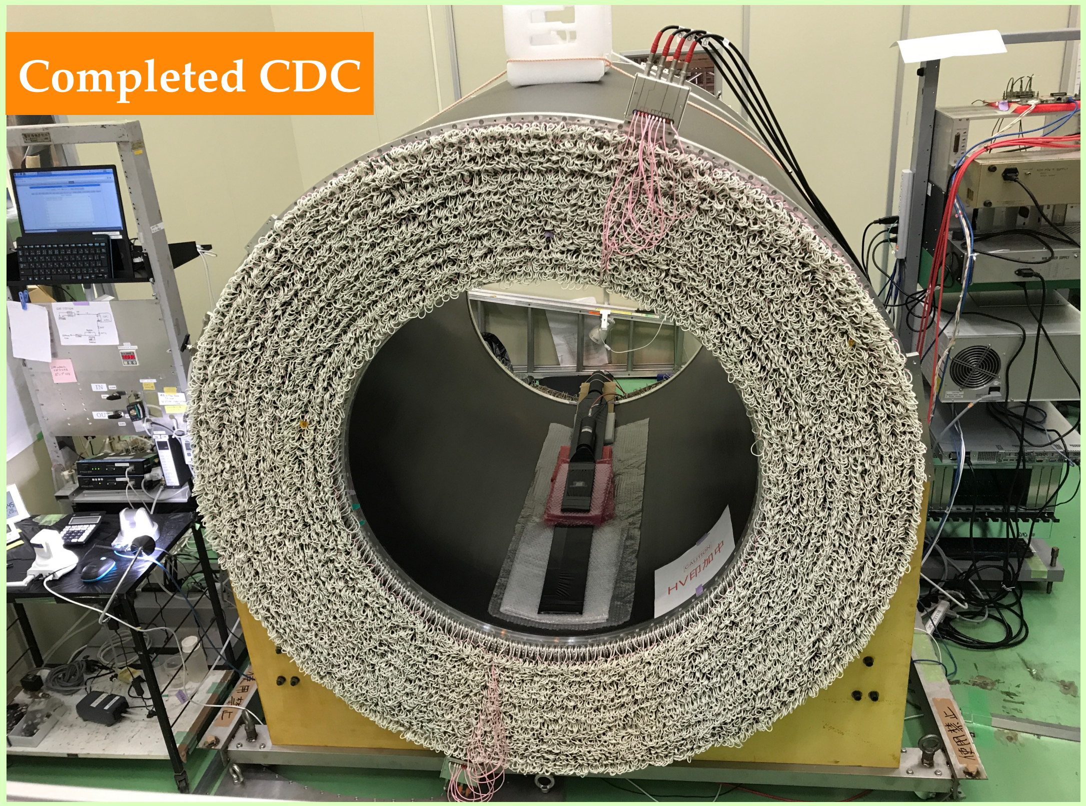


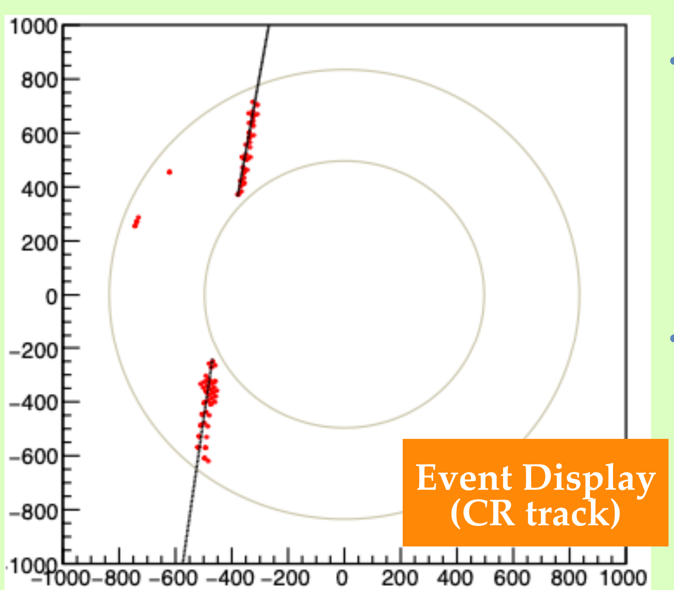
Solution for this small leakage was found, and verified in MR. Next test, under preparation.

Proposal for next test, submitted.

Current Status (3) — Detector Construction —

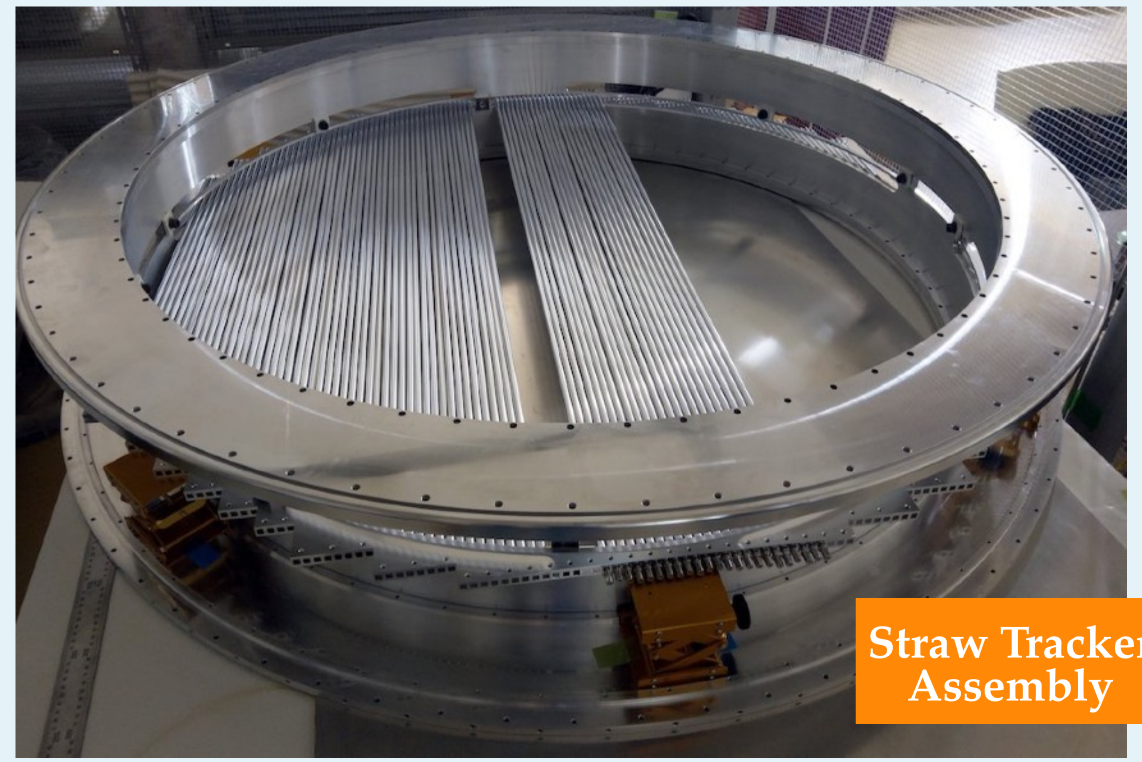
CyDet (for μ-e conv. search)





- CDC, completed and under commissioning with cosmic-ray.
- Trigger hodoscope is under development.

StrECAL (for beam measurement)



- Straw 1st station is under construction, will be completed soon.
- Five stations will be constructed in total.

- ECAL prototype successfully completed.
- Detector assembly will start soon.

Schedule

- **Construction on all items are ongoing at a fast pace.**
  - **Facility;**
    - **Proton beam line. C-Line construction started and will be completed in 2021. First beam is expected in 2022.**
    - **Transport line (π/μ). Transport solenoid, completed. Pion capture will be completed in 2022. All parts will be ready in early 2023.**
  - **Detector;**
    - **CyDet. CDC, completed and under commissioning. Trigger hodoscope construction will follow.**
    - **StrECAL. Straw tracker, 1st station is under construction, and all five stations will be completed by 2022. ECAL, detector assembly will start soon and will be completed by 2022.**
  - **Accelerator;**
    - **Dedicated 8 GeV operation test was conducted in 2018. Good extinction was confirmed. Next test is under preparation.**
- **As soon as C-Line and radiation shield will be completed (expected in 2022), proton beam commissioning will start. It will be followed by the engineering and physics runs of COMET Phase-I.**

— Conclusions —

- New μ-e conversion search experiment at J-PARC, COMET
  - Two-staged approach; Phase-I will measure beam and search for μ-e conversion with intermediate sensitivity of $O(10^{-15})$. Phase-II will search for μ-e conversion with full sensitivity of $O(10^{-17})$.
  - Complement with $\mu \to e\gamma$ / $\mu \to eee$ search, to explore new physics BSM.
  - Can achieve TeV-scale, even higher, by achieving better BR sensitivity.
- Construction (facility, beam line, detectors) are ongoing
  - Dedicated proton beam line will be completed in 2021. 1st beam will be delivered in 2022.
  - Transport beam line will be completed in 2022, expected to be ready in 2023.
  - Detector construction is ongoing. (CDC, completed. Straw, under construction. ECAL, assembly will start soon)
  - Accelerator test, conducted in 2018. Satisfied extinction was confirmed. Next test is under preparation to improve the beam extinction.
- As soon as proton beam line will be completed, proton beam commissioning will start. It will be followed by the engineering and physics runs of COMET Phase-I.

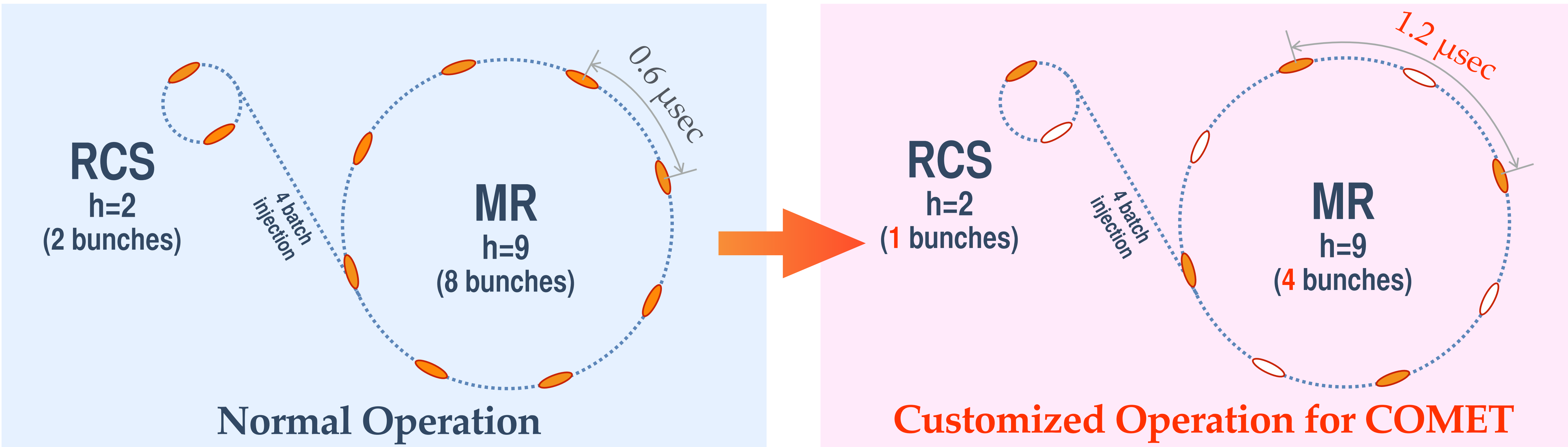
backups

J-PARC

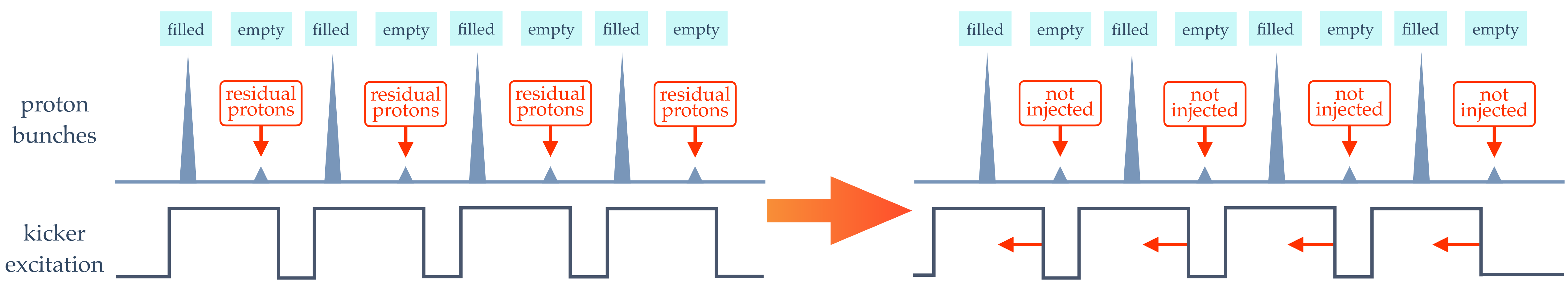

Hadron Experiment Facility
Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)
Accelerator-driven
Transmutation exp facility
Neutrino Experiment Facility
(T2K, towards SK)
Linac
(330m, 400MeV)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

How to satisfy COMET requirements on proton beam

How to realize Longer Bunch Separation

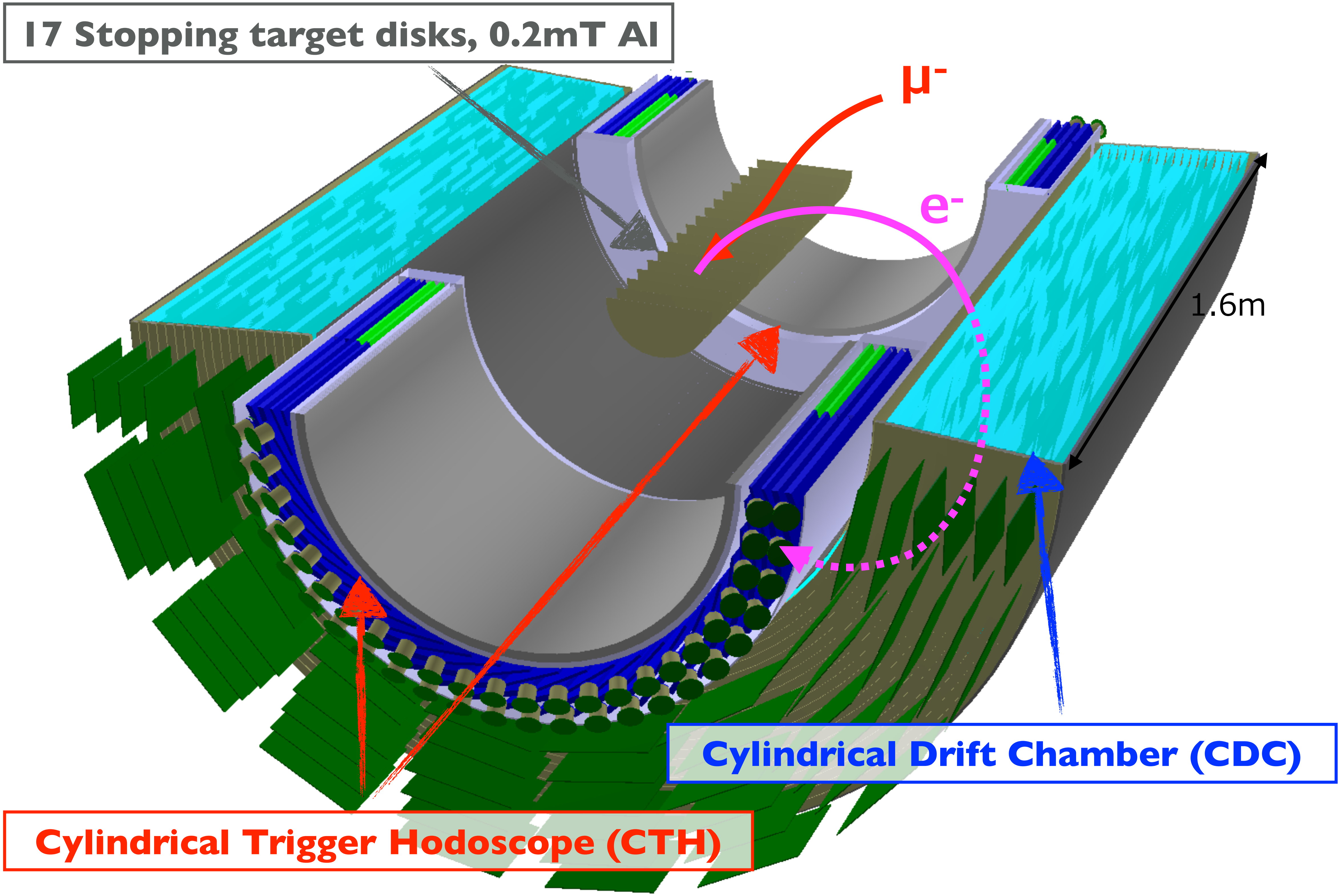


How to realize Excellent Extinction

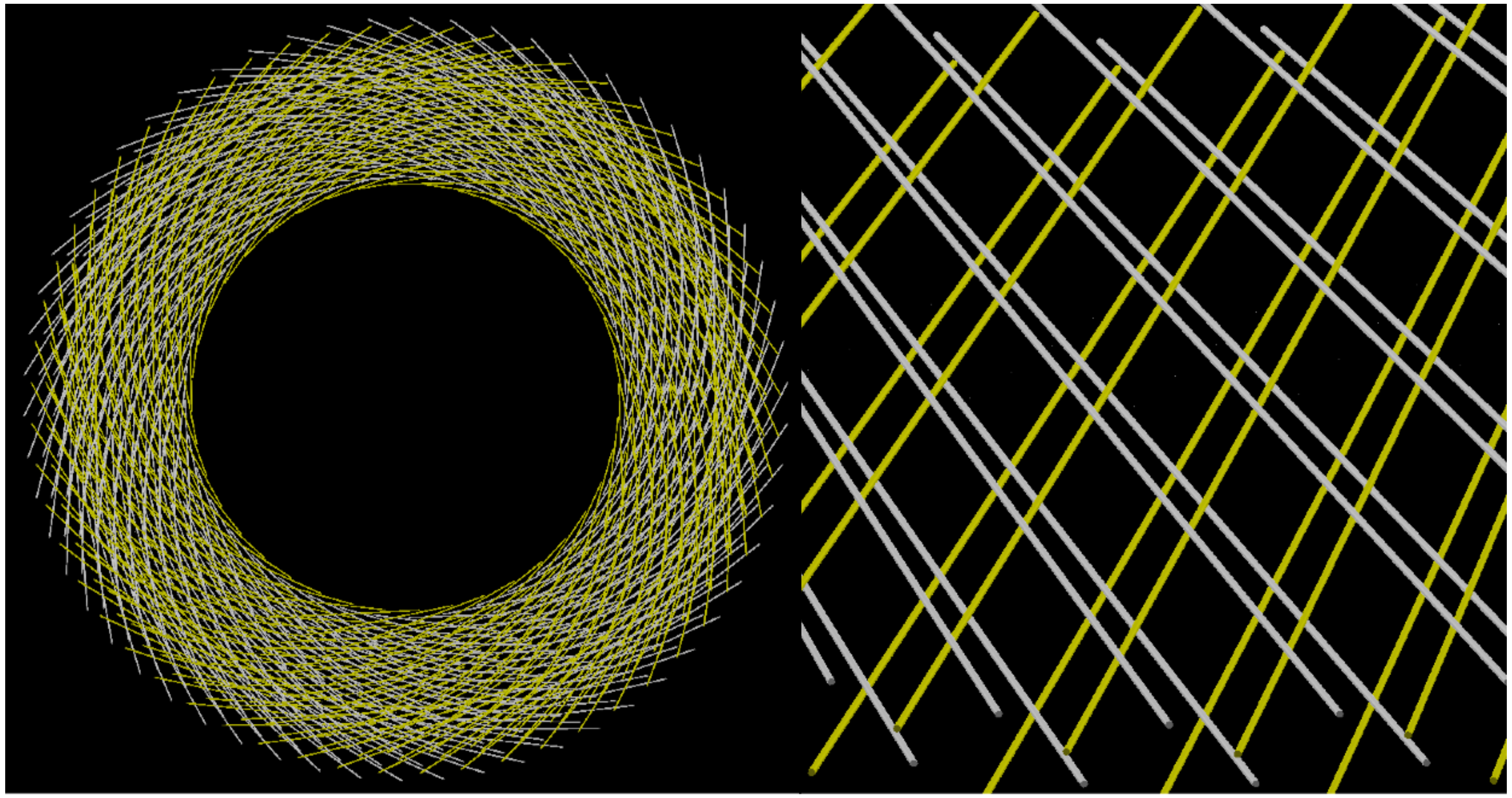


- 4 batch injection = 4 times kicker excitation
- **Initial Extinction** = ***O*(-6)** due to "Chopper Inefficiency"
- Shift the kicker timing by half a period forward
- "Single Bunch Kicking" → **Perfect Extinction !!**

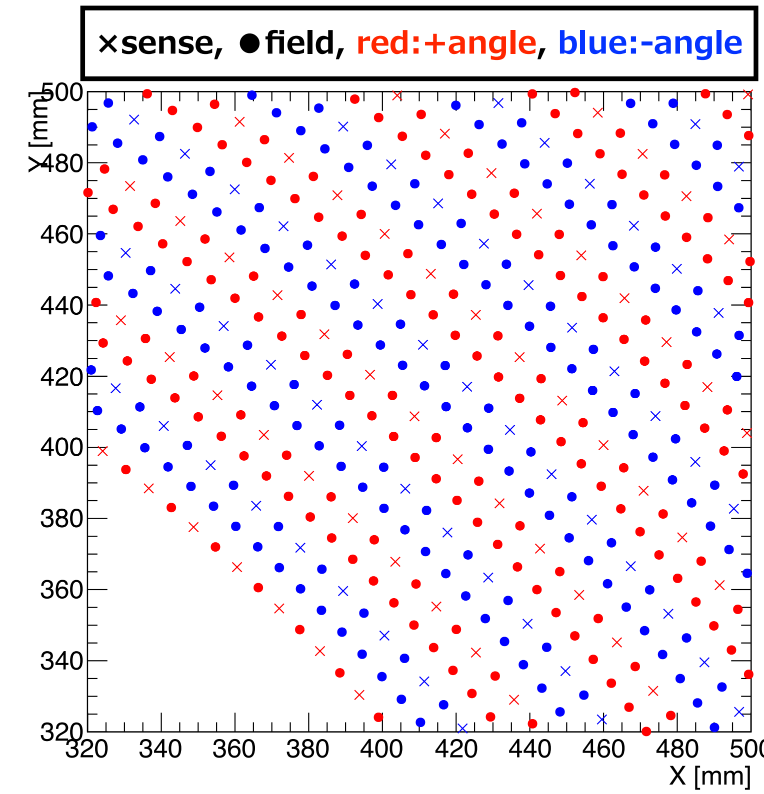
CyDet : Cylindrical Detector System



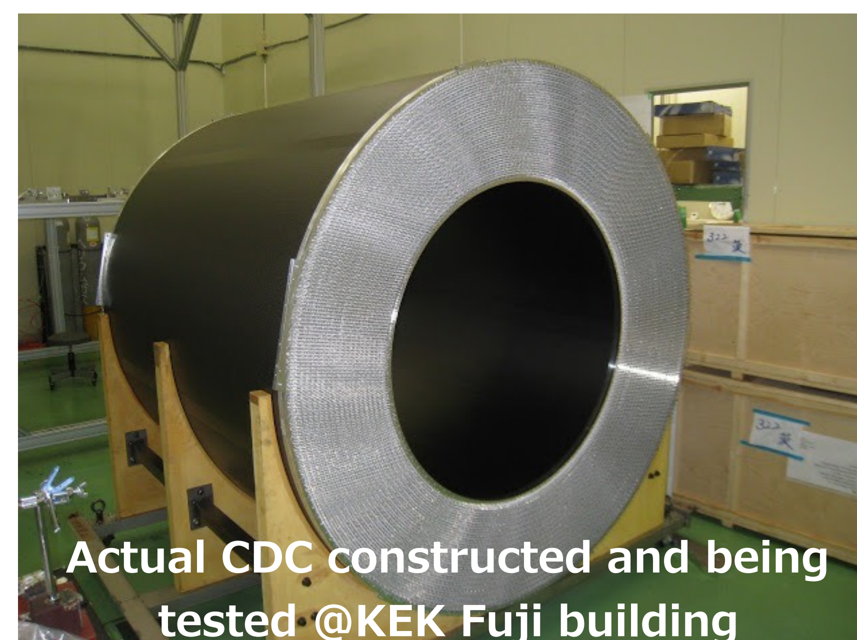
CDC : Cylindrical Drift Chamber (1/2)



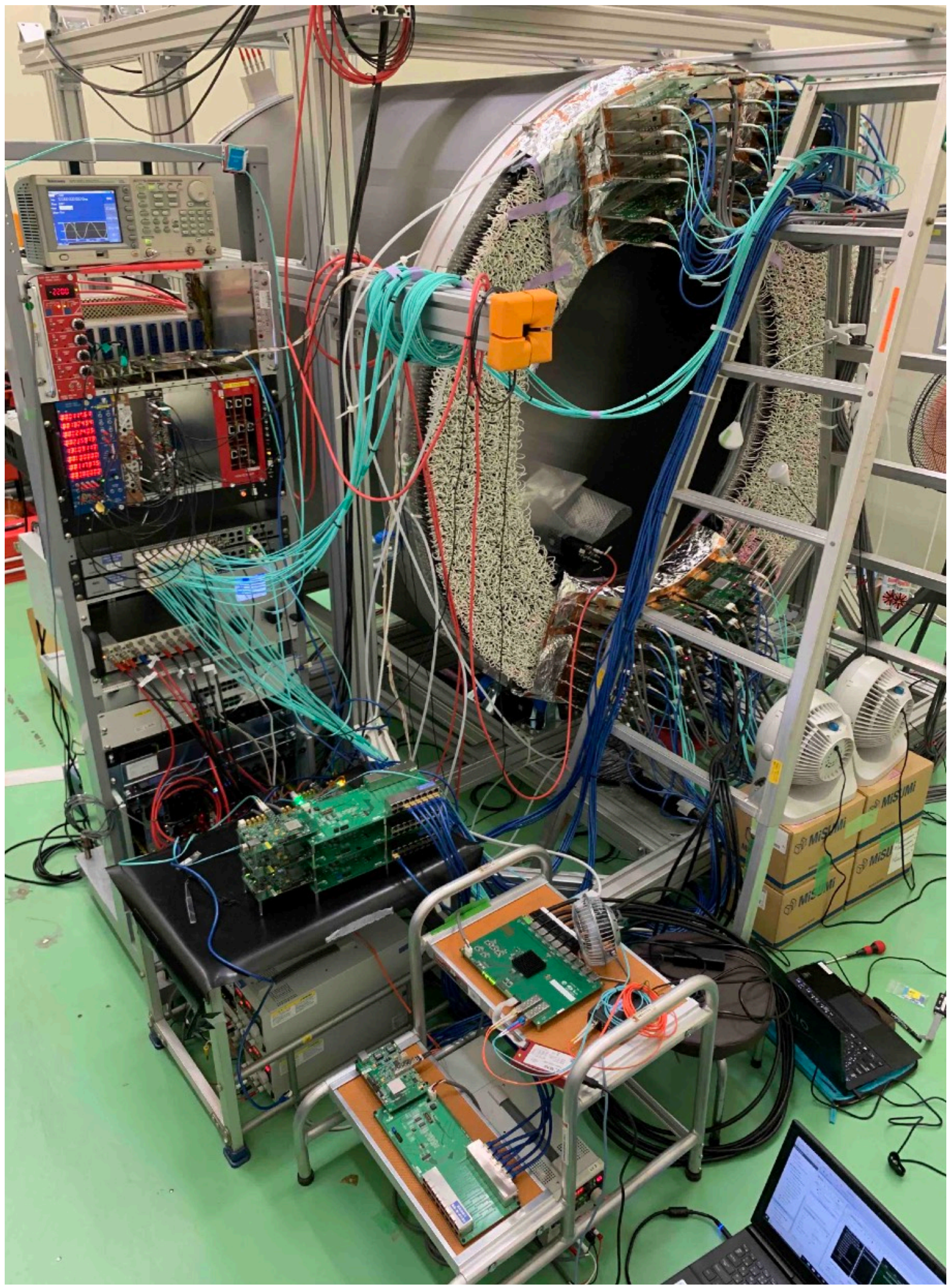
※Not in the correct scale & wire configurations



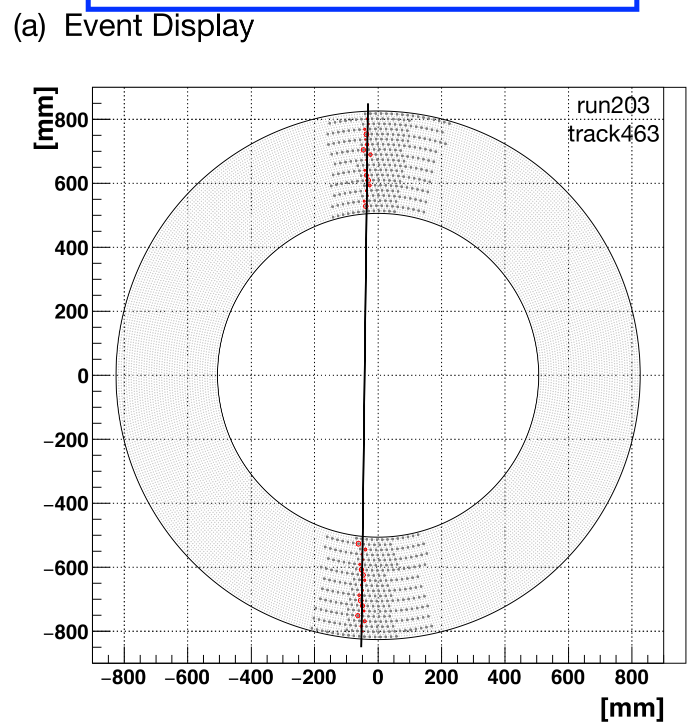
- Main tracking detector for the Phase-I physics measurement
- He:iC_4H_{10}=90:10 based on the MC&prototype studies
- All stereo wires to measure the 3D momentum
- 18 layers (+2 guard layers), ~5k sensitive wires
  - Sense: Au plated W, 25μmφ, Field: Al 126μmφ
- A 0.5mmT CFRP inner wall to reduce the proton BG

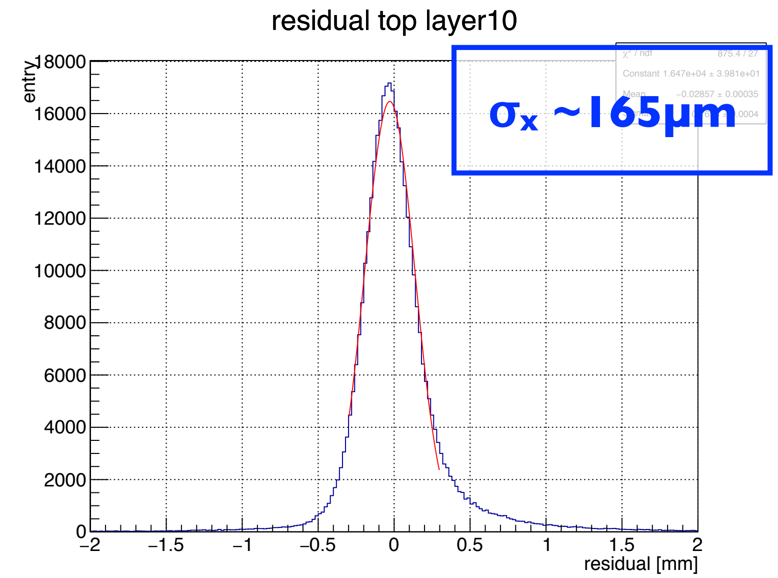

Actual CDC constructed and being tested @KEK Fuji building

CDC : Cylindrical Drift Chamber (2/2)



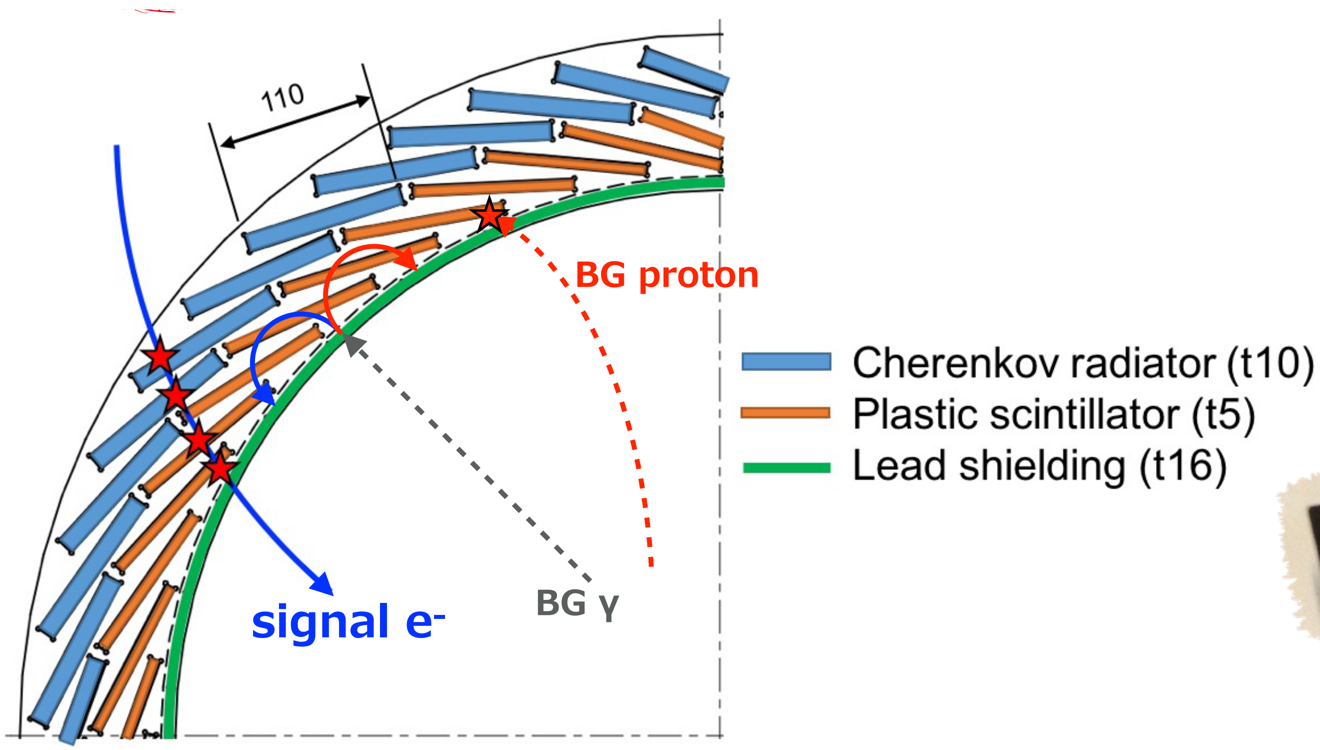
An example of cosmic-ray event

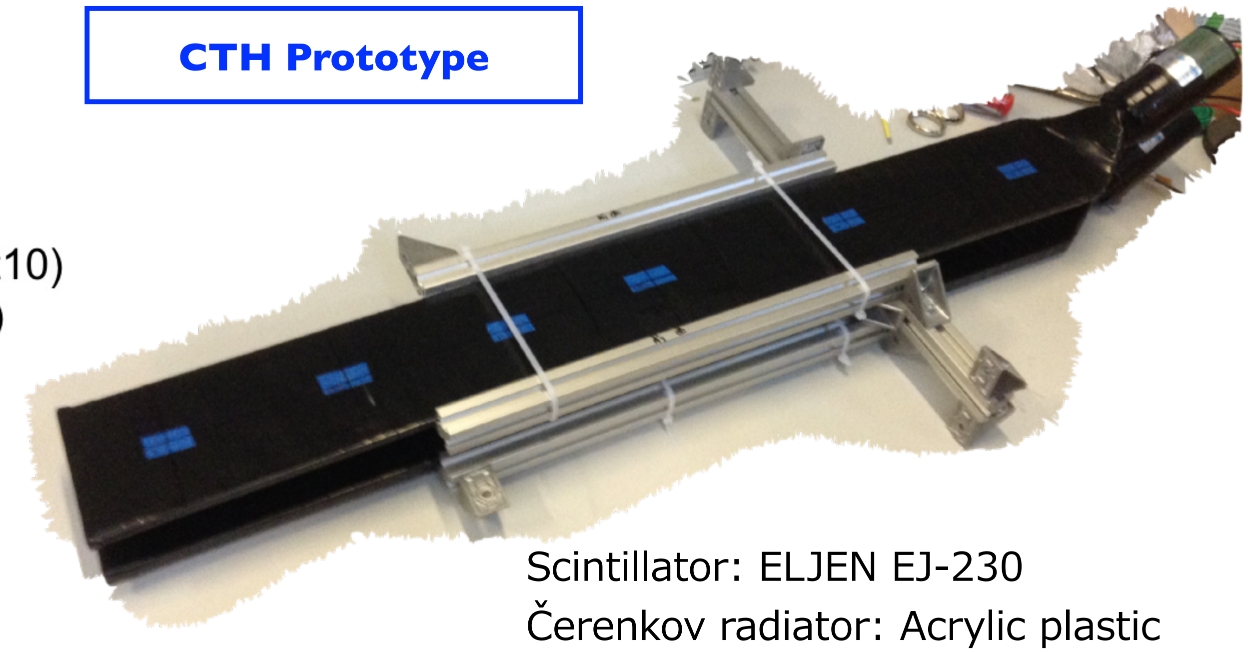




- Detector has been constructed and being tested using cosmic-rays @KEK Tsukuba
- Detector shows excellent stability after the construction >2-y ago
- Spatial resolution of **165μm** has been confirmed
- Almost ready to transport to J-PARC

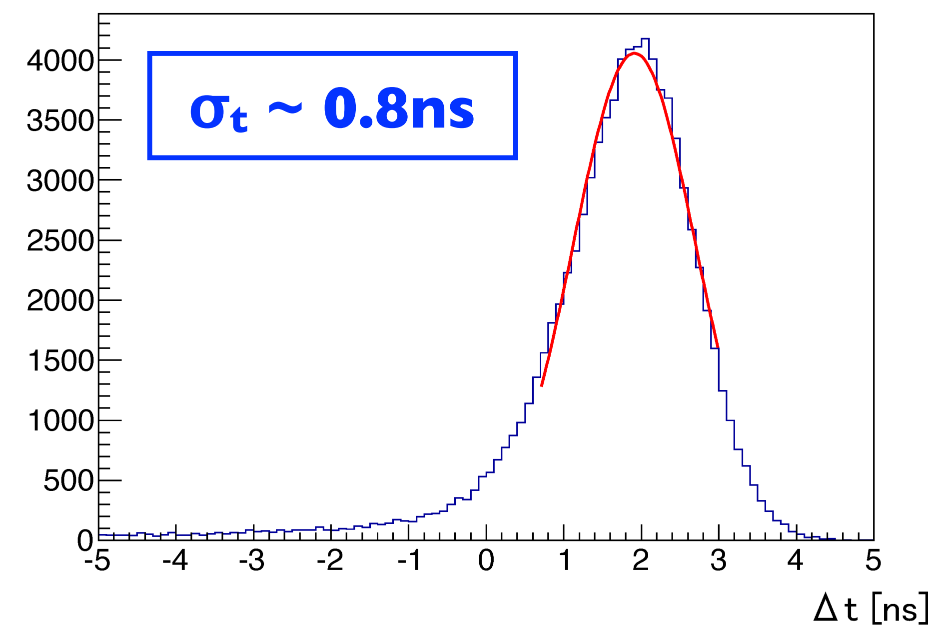
CTH : Cylindrical Trigger Hodoscope



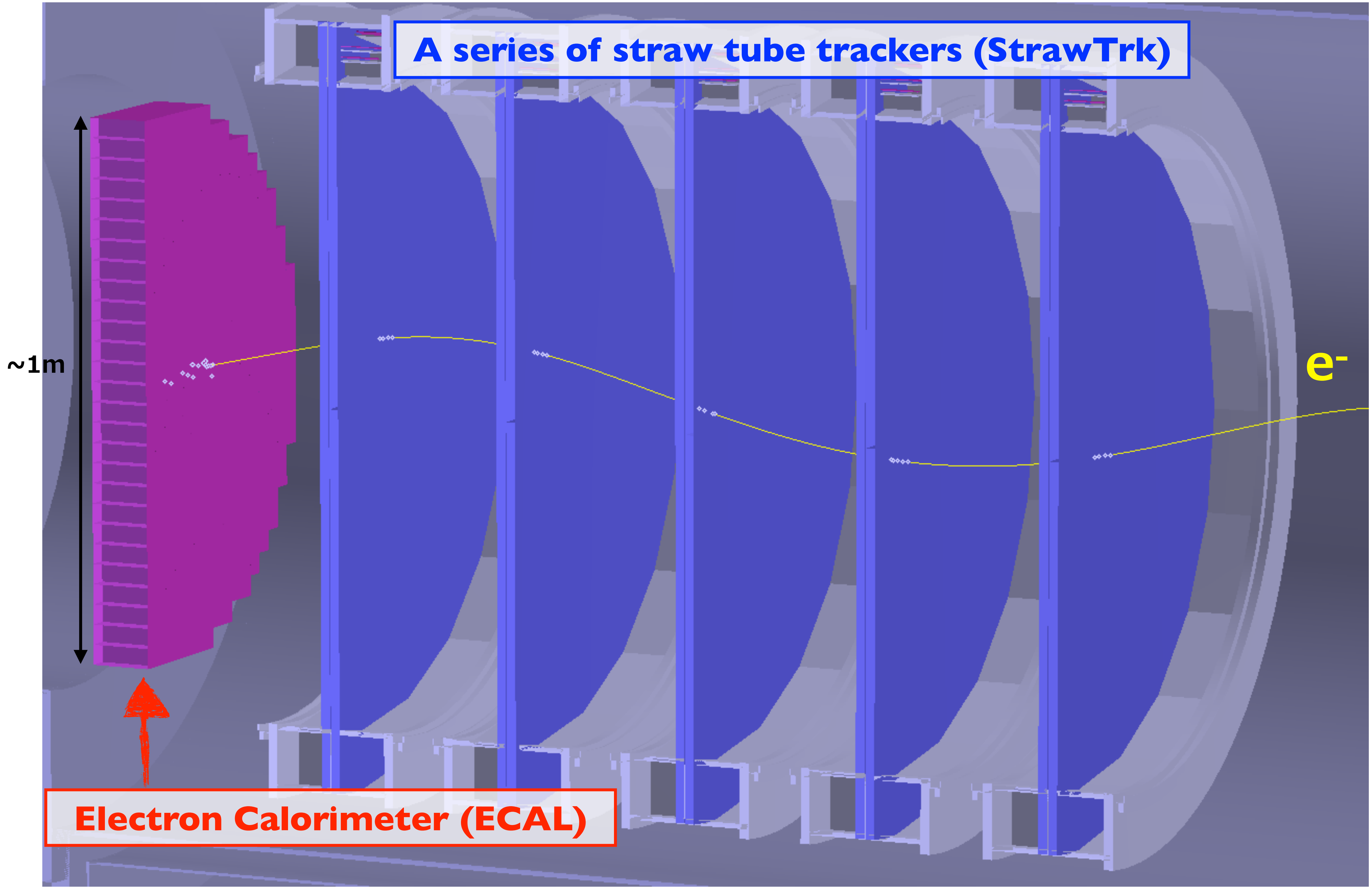


Scintillator: ELJEN EJ-230
Čerenkov radiator: Acrylic plastic
PMT: Hamamatsu H8403-70

- Determine the primary trigger and precise T0 value within the 1ns precision
- 64 or 48 plastic scintillators/acrylic Čerenkov radiators cylindrically aligned both upstream/downstream
- A Čerenkov layer reject all low-β particles (<0.65)
- Use the magnetic field tolerable fine-mesh PMTs
- 4-fold coincidence strongly suppresses the accidental pileups
- Final detector design is almost fixed



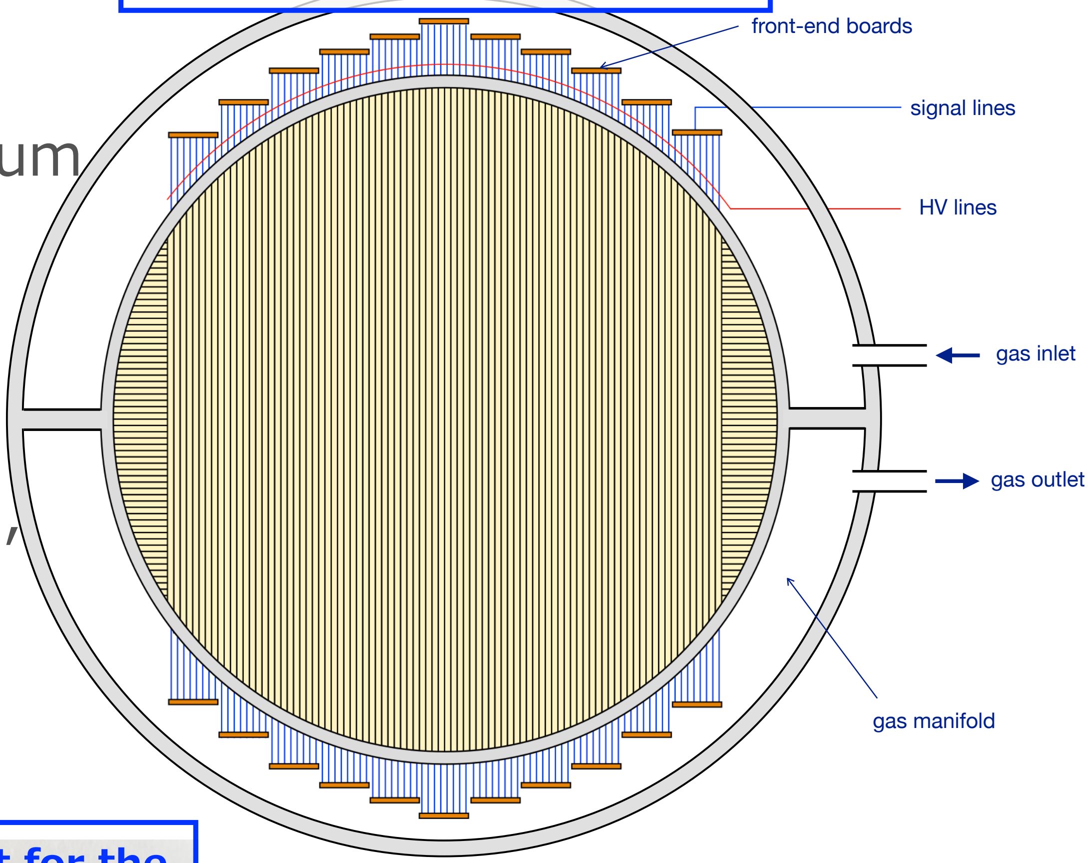
StrECAL : Straw tracker and Electromagnetic Calorimeter

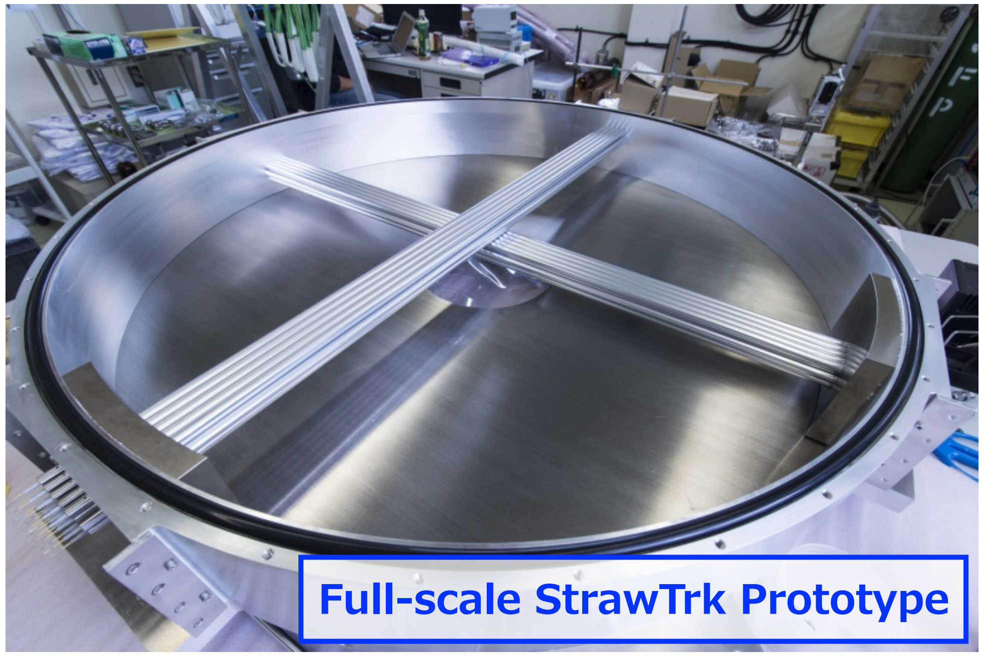


Straw Tracker (1/3)

- Main tracker for Phase-I beam measurement & Phase-II physics run
- Ultra thin straw-tube chambers operational in Vacuum
  - 20μmT/10mmφ for Phase-I
  - 12μmT/5mmφ for Phase-II
  - Ar:C_2H_5=50:50
  - Each "station" consists of 240(~500) straws ×2, 5(>6) stations for Phase-I (Phase-II)
- Large prototype was constructed to evaluate the detector performance and to finalise the design

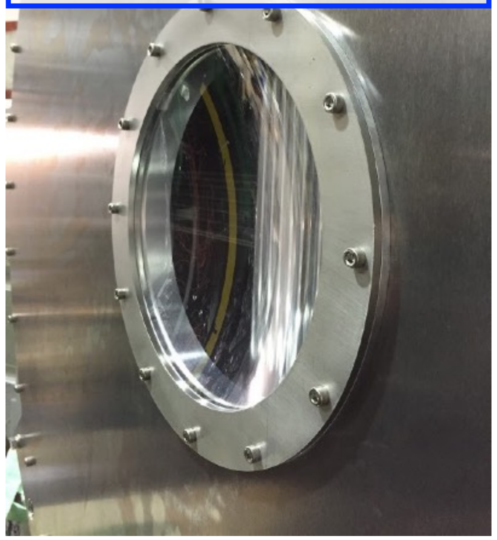
A station of straw tracker



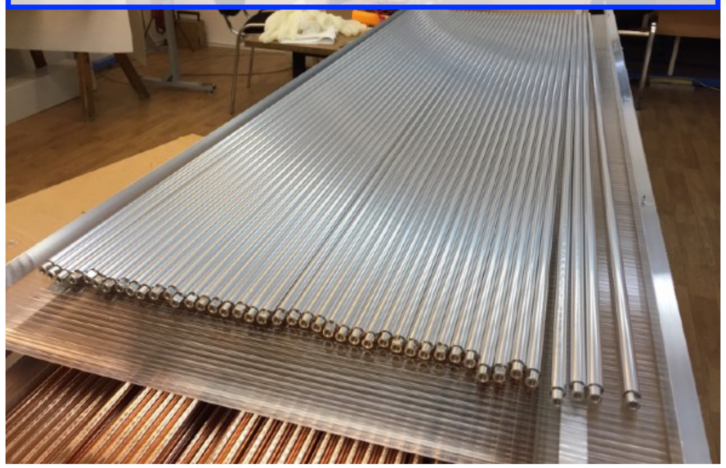


Full-scale StrawTrk Prototype

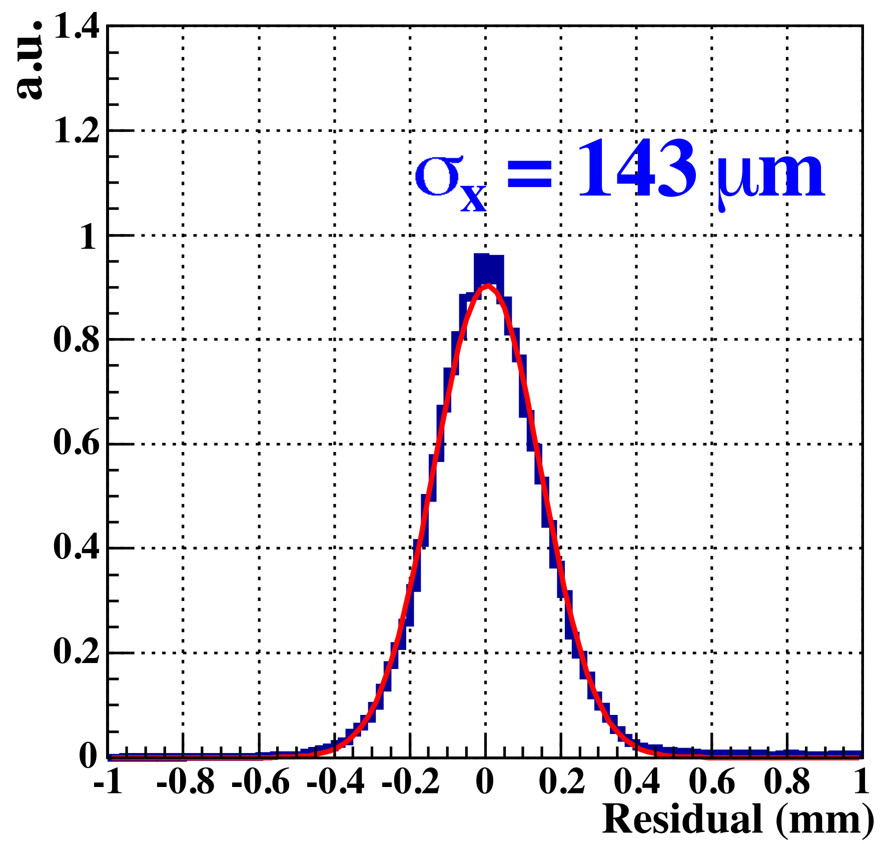
Vacuum test for the full-scale prototype

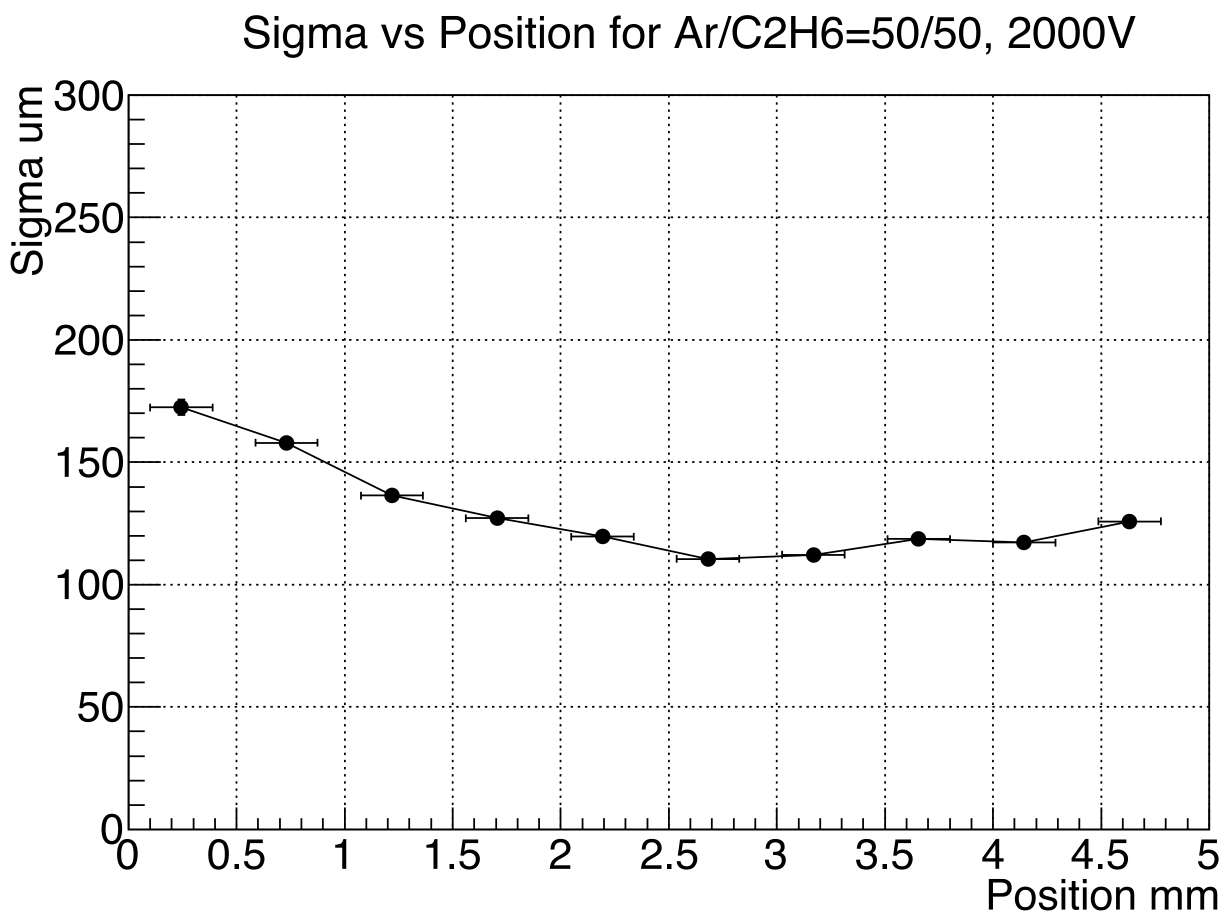


All Straw tubes manufactured for Phase-I



Straw Tracker (2/3)





- Vacuum tightness has been proven down to 0.1Pa
- Spatial resolution better than **150μm** has been confirmed with the StrawTrk Phase-I full-scale prototype
- Detector design has been fixed based on these studies
  - Construction of Phase I Straw Tracker is Ongoing

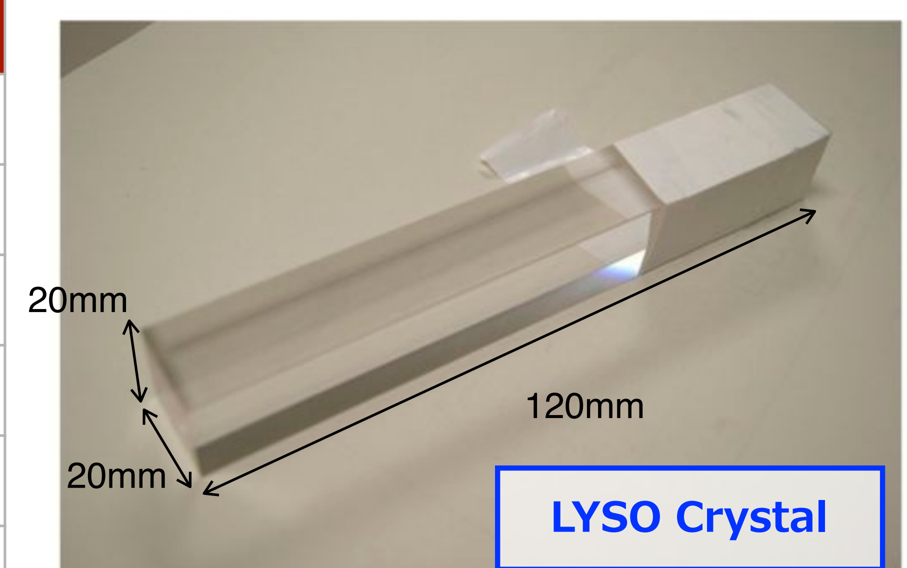
Straw Tracker (3/3)

- Phase-II straw tube is under development in parallel
- Succeeded to manufacture **12µm** thick/ 5mmφ straw tubes
- Achieve the vacuum tightness against 4 bar pressure
- Further studies are ongoing

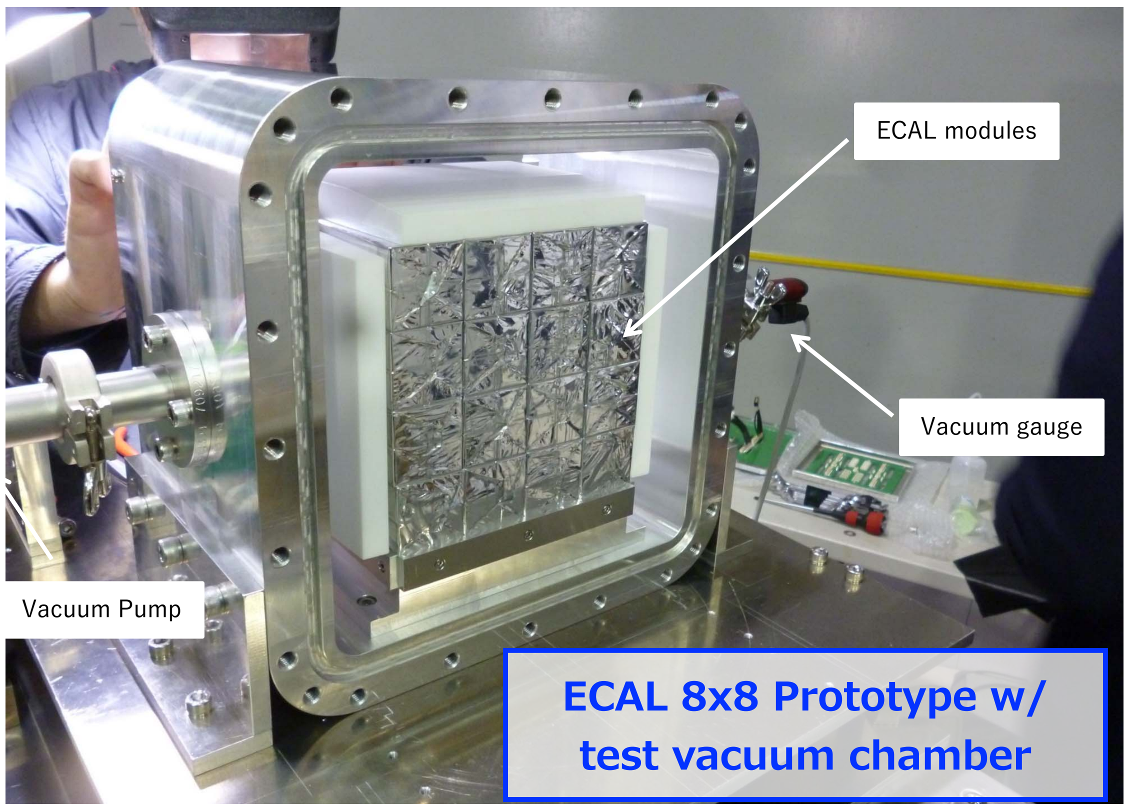
ECAL (1/2)

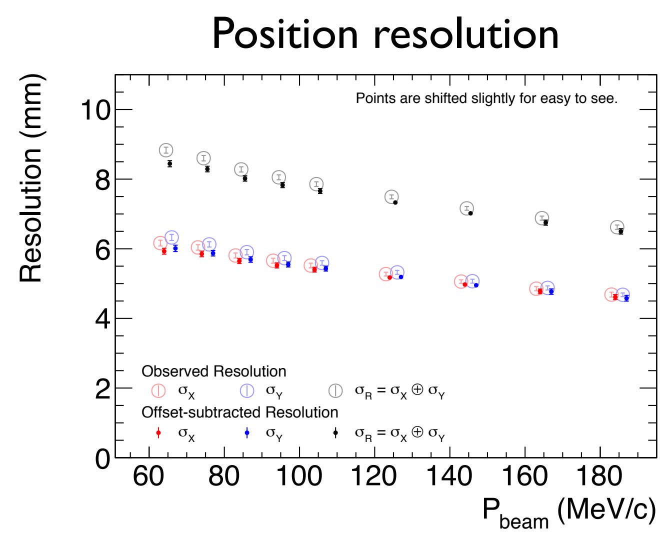
- Measure the energy and timing of particles
- Provide the trigger signal
- Located inside the 1T magnetic field &<10Pa vacuum
- 500-1,000(~2,000) LYSO crystals for Phase-I(Phase-II)
    - Fast time response + high light yield
- Cost-effective/B-field tolerant APDs (Hamamatsu S8664-1010 10×10mm^2) to read-out the scintillation light

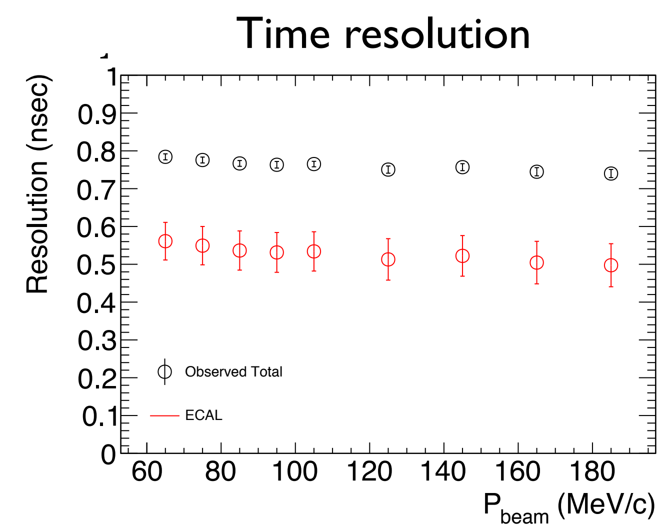
	GSO(Ce)	LYSO	PWO	CsI(pure)
Density (g/cm^3)	6.71	7.40	8.3	4.51
Rad. length (cm)	1.38	1.14	0.89	1.89
Moliere radius (cm)	2.23	2.07	2.00	3.57
Decay constant (ns)	600^s,56^f	40	30^s,10^f	35^s,6^f
Wave length (nm)	430	420	425^s,420^f	420^s,310^f
LY (NaI(Tl)=100)	3^s,30^f	83	0.08^s,0.29^f	3.6^s,1.1^f

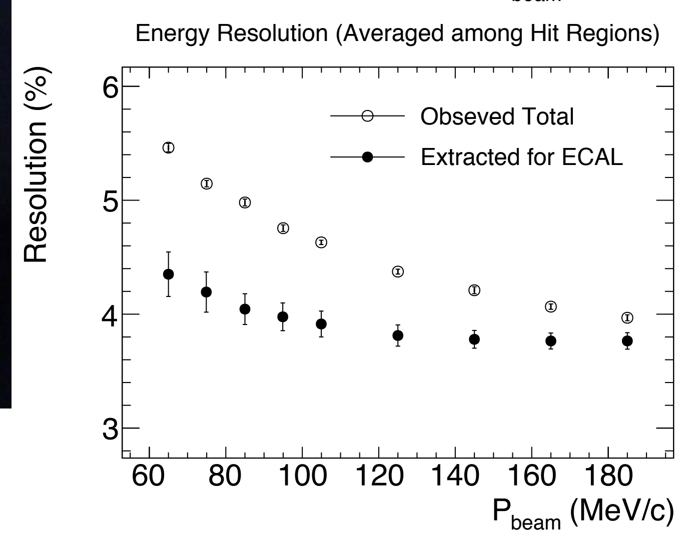


ECAL (2/2)



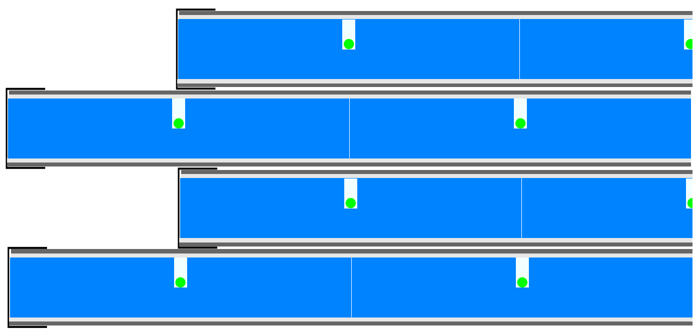






- Succeed to operate the ECAL prototype inside the vacuum
- In the beam test using mono-energetic electron beam, the prototype showed an excellent performance that satisfies our requirements
  - **σ_E/E 4%**, **$\sigma_{x/y}$ <6mm**, **σ_t 0.5ns** @105MeV e-
  - Scalable to the actual detector ☞ final design for Phase-I has been almost fixed

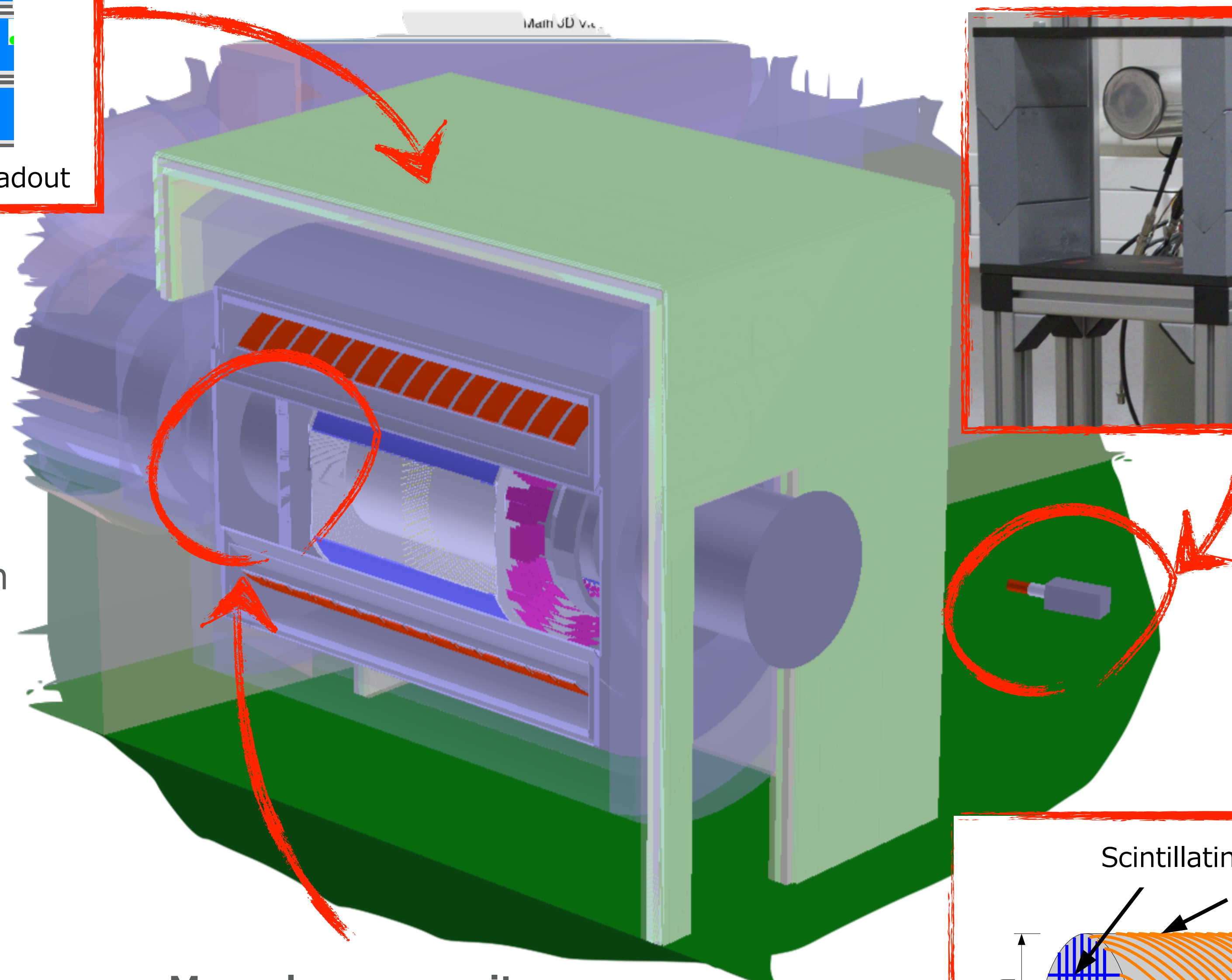
Other detector systems



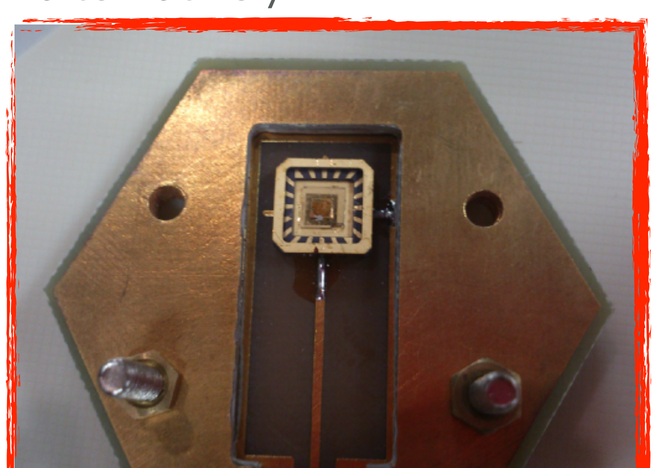
Plastic Scintillator+WLS fibre ×4 layers, SiPM readout

Cosmic-ray Veto (CRV)
- Inefficiency less than 0.4%
- Radiation tolerance @10^{11} n/cm^2

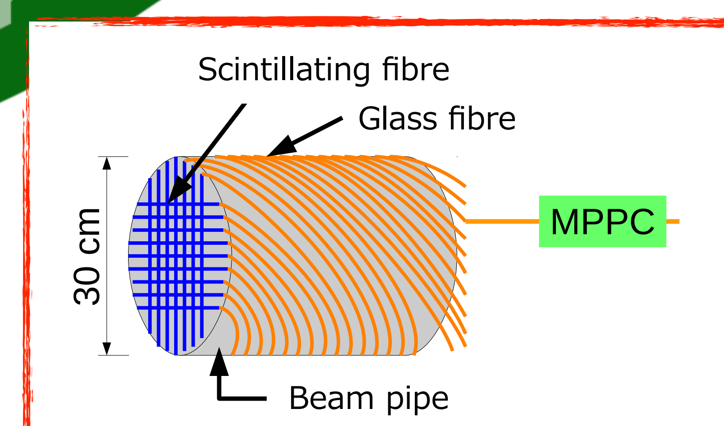
Germanium Detetor (GeDet)
- Measure the muonic X-ray to determine the precise normalisation factor
- A prototype detector has been developed



Extinction Monitor
- Diamond detector has shown excellent performance to distinguish the single leakage proton in-between high-intense proton bunches
- GaN detector also being considered alternatively

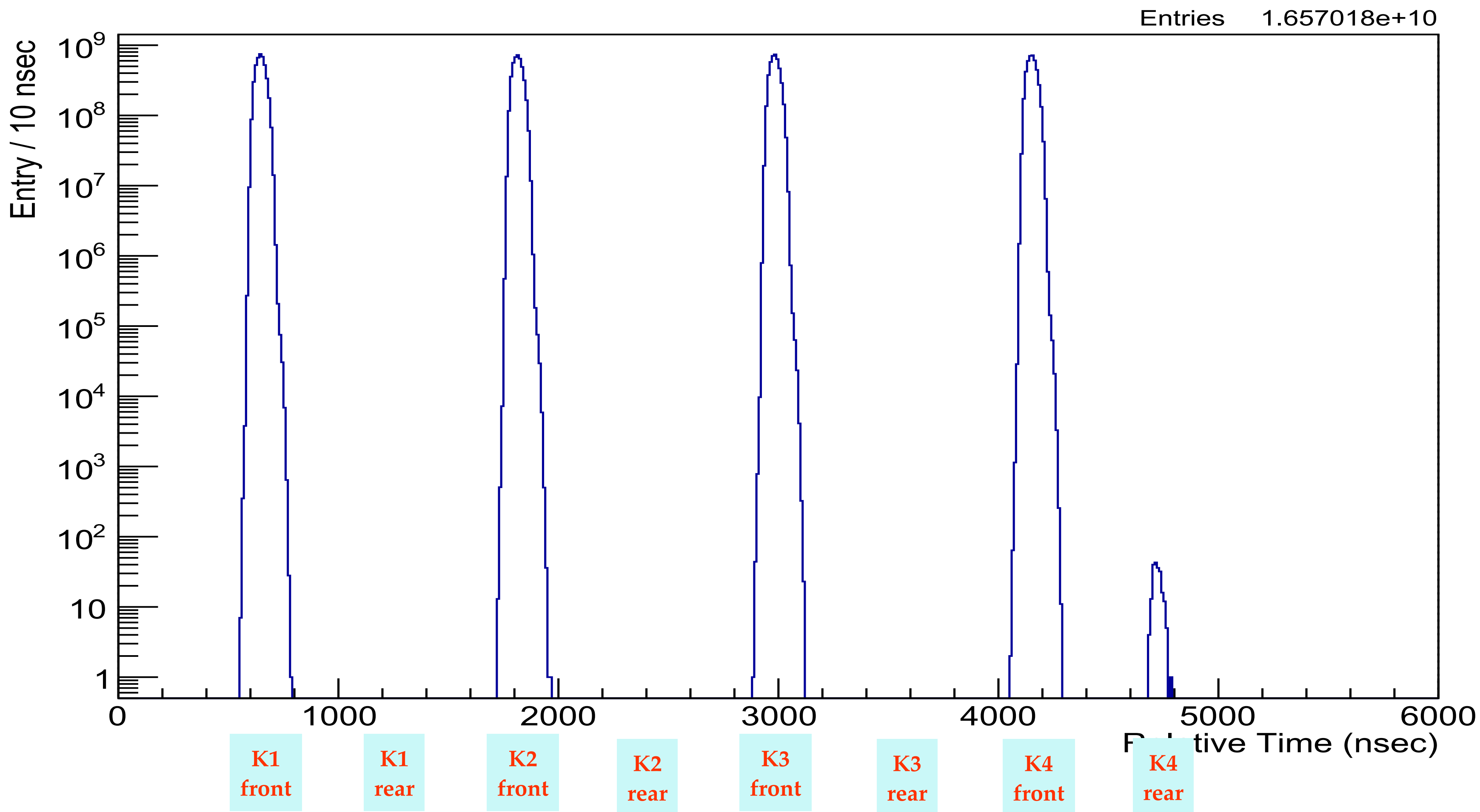


Muon beam monitor
- Can provide the timing and beam profile at the end of the curved solenoid
- Still under the discussions/R&D



Extinction at Hadron with Bunched-SX beam

- **Result with kicker shift to realize an excellent extinction**



- Front buckets were filled with protons of COMET intensity (1.6×10^{12} ppp) and Injection Kicker was shifted 600 nsec forward
- **Perfect Extinction (= No Leak)** was realized for 3 Injection Batches (K1, K2 and K3)
- But…
    - Small amount of residual protons are shown in K4 rear…

Next 8 GeV operation test

- Proposal, submitted to J-PARC Particle Nuclear Experiments PAC (Program Advisory Committee) in June 2020
- To request 6 days of beam time
- Joint collaboration with J-PARC accelerator group and COMET experimental group
- Test items;
  - Optimize Accelerator-operation
  - Improve Beam-loss
  - Improve Extraction-efficiency
  - Improve Extinction
  - Extinction measurement
  - Proton beam monitor test

Proposal for

8 GeV Operation Test and Extinction Measurement

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June 2020

Abstract

We request 6 days of beam time for the COMET experiment to perform **an 8 GeV operation test** of the J-PARC MR and **an extinction measurement** at the abort line of the MR and the secondary beam line of the Hadron Experimental Facility. A beam energy of 8 GeV instead of normal 30 GeV of MR is required by the COMET experiment, and excellent inter-bunch beam extinction is essential in order to achieve the target sensitivity of COMET. The proposed campaign consists of two parts; "an accelerator study" and "an inter-bunch extinction measurement". Both studies were originally carried out in the previous 8 GeV campaign in January and February 2018. Through the present studies, we aim to improve the quality of the 8 GeV proton beam, building on the knowledge obtained in the previous campaign.

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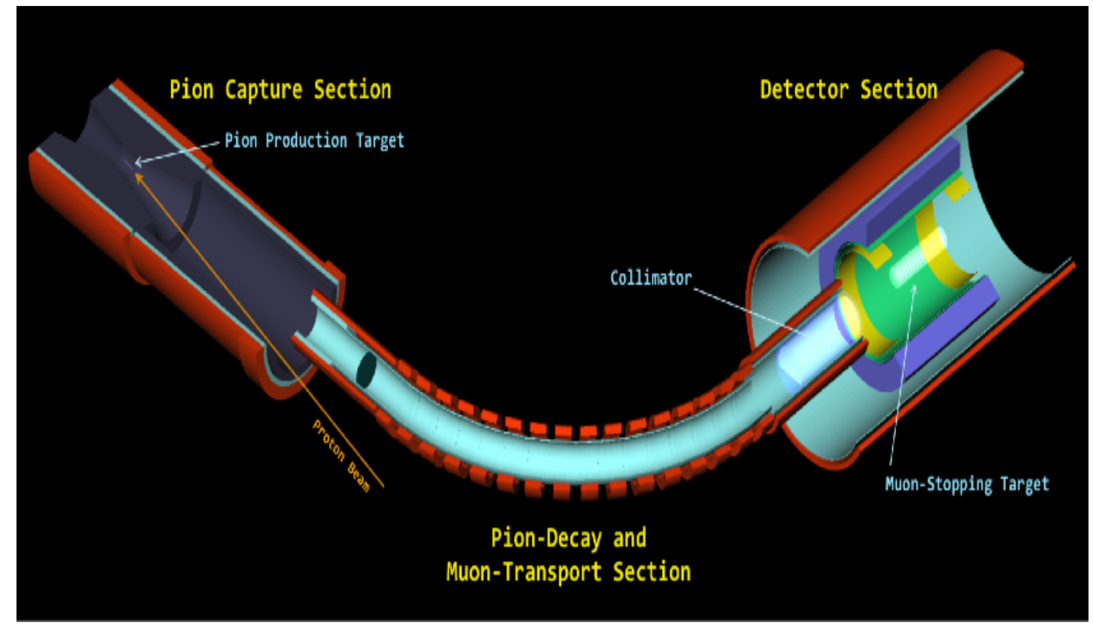
1

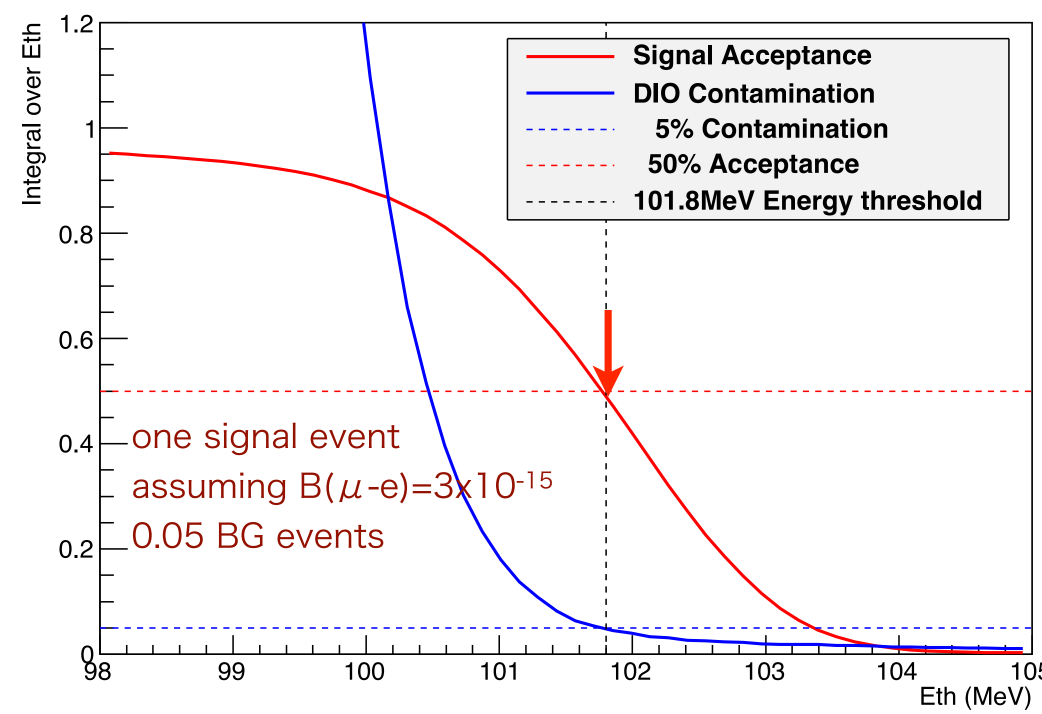
Sensitivity Estimation for Phase-I

- 8GeV, 3.2kW proton beam is assumed
  - 2.5×10^{12} protons/sec
  - 10^{-10} of extinction is supposed
- 150 days (1.2×10^{7} sec) running time
- Expected single event sensitivity

$$\mathcal{B}(\mu^- + \mathrm{Al} \to \mathrm{e}^- + \mathrm{Al}) = \frac{1}{N_\mu^{stop} \cdot f_{cap} \cdot \mathcal{A}_{\mu-e}}$$

  - $\mathcal{B}(\mu+\mathrm{Al}\to\mathrm{e}+\mathrm{Al}) = 3.1\times10^{-15}$
- Upper limit at 90% C.L.
  - $\mathcal{B}(\mu+\mathrm{Al}\to\mathrm{e}+\mathrm{Al}) < 7.0\times10^{-15}$
  - *cf.* present limit $< 7\times10^{-13}$ (SINDRUM-II)





Expected backgrounds for 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
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Summary of COMET Phase-I & Phase-II

	COMET-Phase-I	COMET-Phase-II
experiment starts (*)	in ~2023	Ready in 3 years after Phase-I completion
beam power	3.2kW (8GeV, 400nA)	56kW (8GeV, 7μA)
running time	150 days	2.0 x 10^7 (sec)
# of protons	3.0 x 10^(19)	8.5 x 10^(20)
# of muon stops	1.5 x 10^(16)	2.0 x 10^(18)
muon rate	5.8 x 10^9	1.0 x 10^(11)
# of muon stops / proton	0.00052	0.00052
# of BG	0.02	0.3
S.E.S.	3.1 x 10^(-15)	2.6 x 10^(-17)
U.L. (90%CL.)	7.0 x 10^(-15)	6.0 x 10^(-17)

* including the engineering run