# StrECAL System for COMET Phase-I & Phase-II

* **StrECAL = Straw tracker + Electromagnetic CALorimeter**


**Hajime NISHIGUCHI, *KEK · J-PARC***
***on behalf of the COMET collaboration***

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- StrECAL System
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  - Electromagnetic Calorimeter
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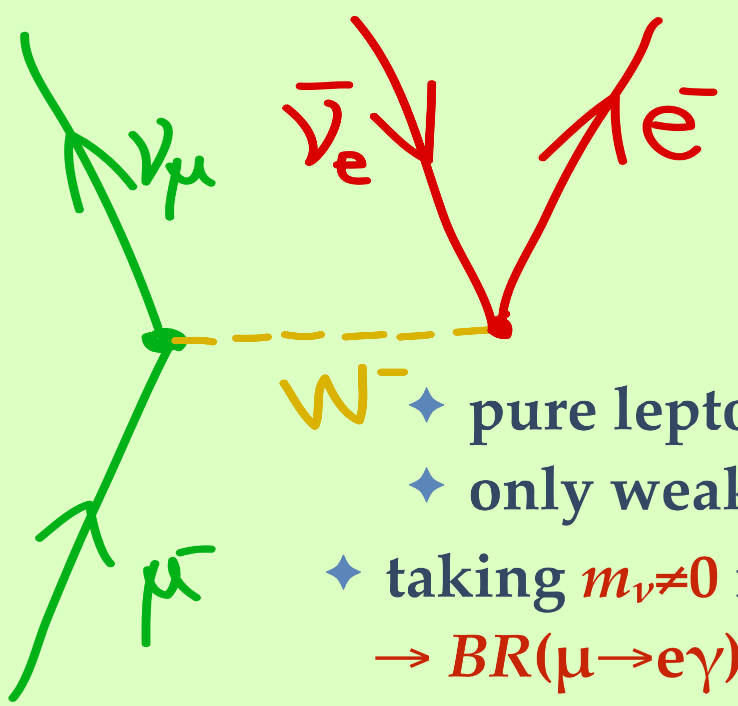
# The COMET Experiment
# to
# Search for $\mu^- N \rightarrow e^- N$ (Mu-E Conversion)

# Search for Charged Lepton Flavour Violation in μ-processes

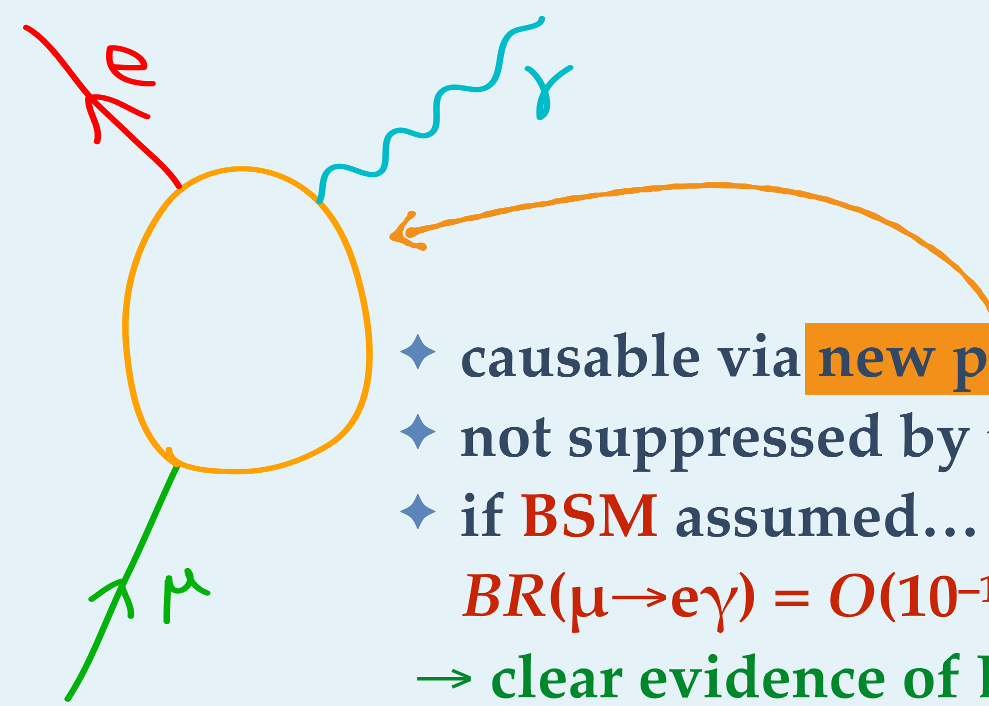
- **Muon is Best Probe to search for CLFV; *eg*. $\mu^+ \to e^+\gamma$, $\mu^- N \to e^- N$, $\mu^+ \to e^+e^+e^-$**

**μ decay in SM**




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

**μ LFV in BSM**

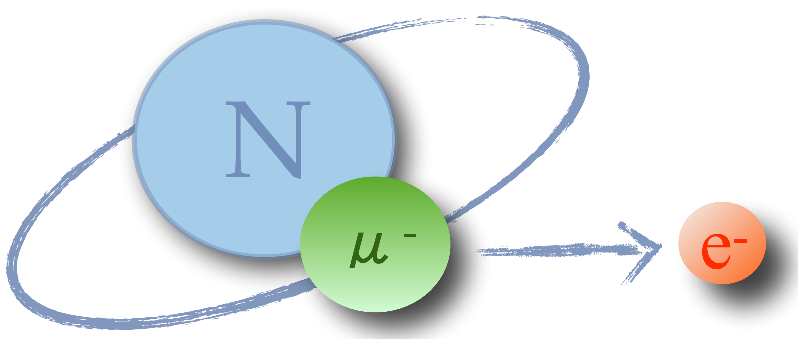



- causable via new particle
- not suppressed by tiny $m_\nu$
- if BSM assumed…
  $BR(\mu \to e\gamma) = O(10^{-16}\text{-}10^{-13})$
  → clear evidence of BSM

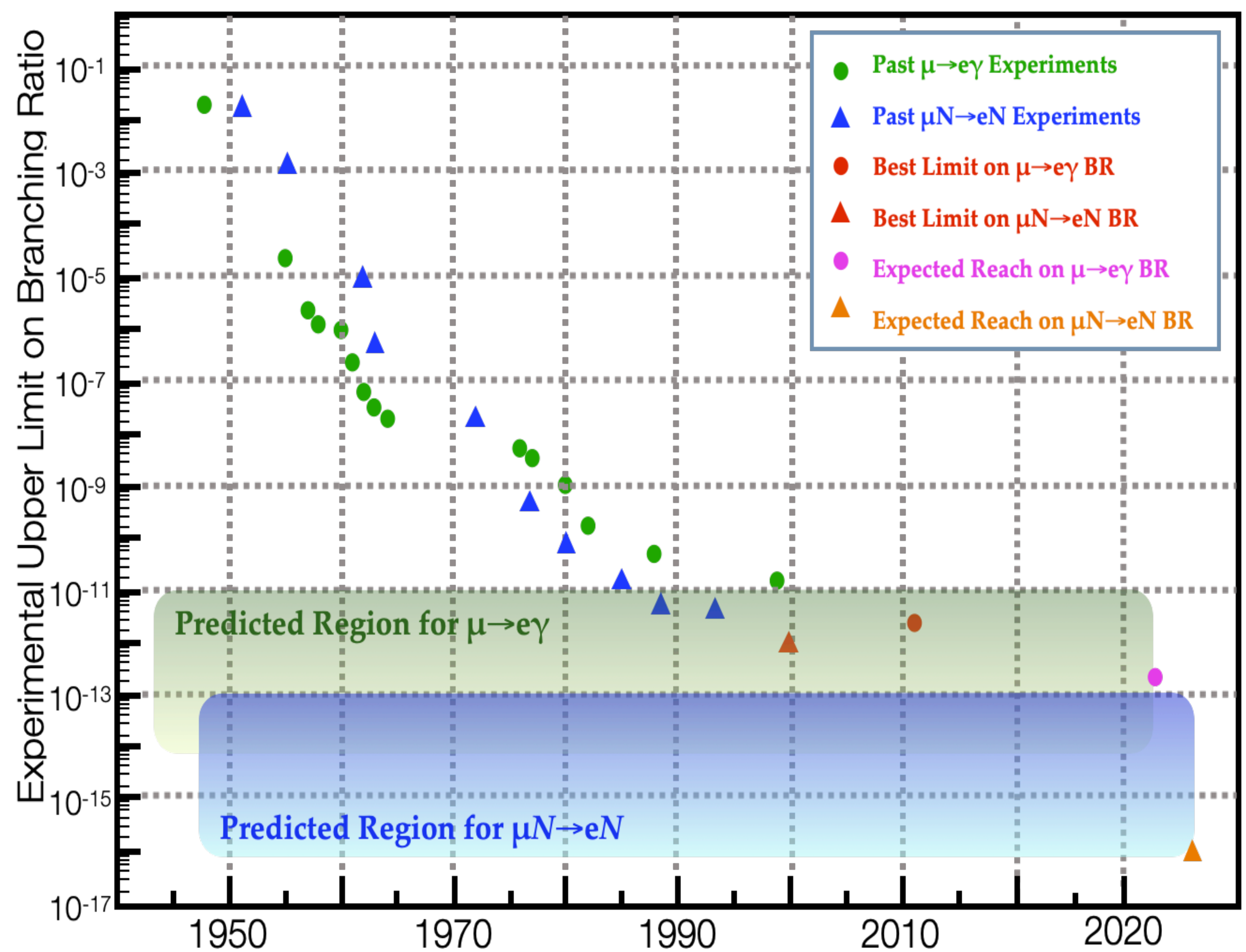
- **Try to Explore New Physics via "*Charged Lepton Flavour Violation*"**
- **Among "Quark", "Neutrino" = Known as Flavour violated**
- **"Charged Lepton Flavour Violation (cLFV)" = Never Observed so far**
  - Very sensitive to the TeV-scale new physics beyond Standard Model
    → **Complementary** and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

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

- "Muon-to-Electron Conversion in Muonic Atom ( $\mu^- N \rightarrow e^- N$ )"
  - 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



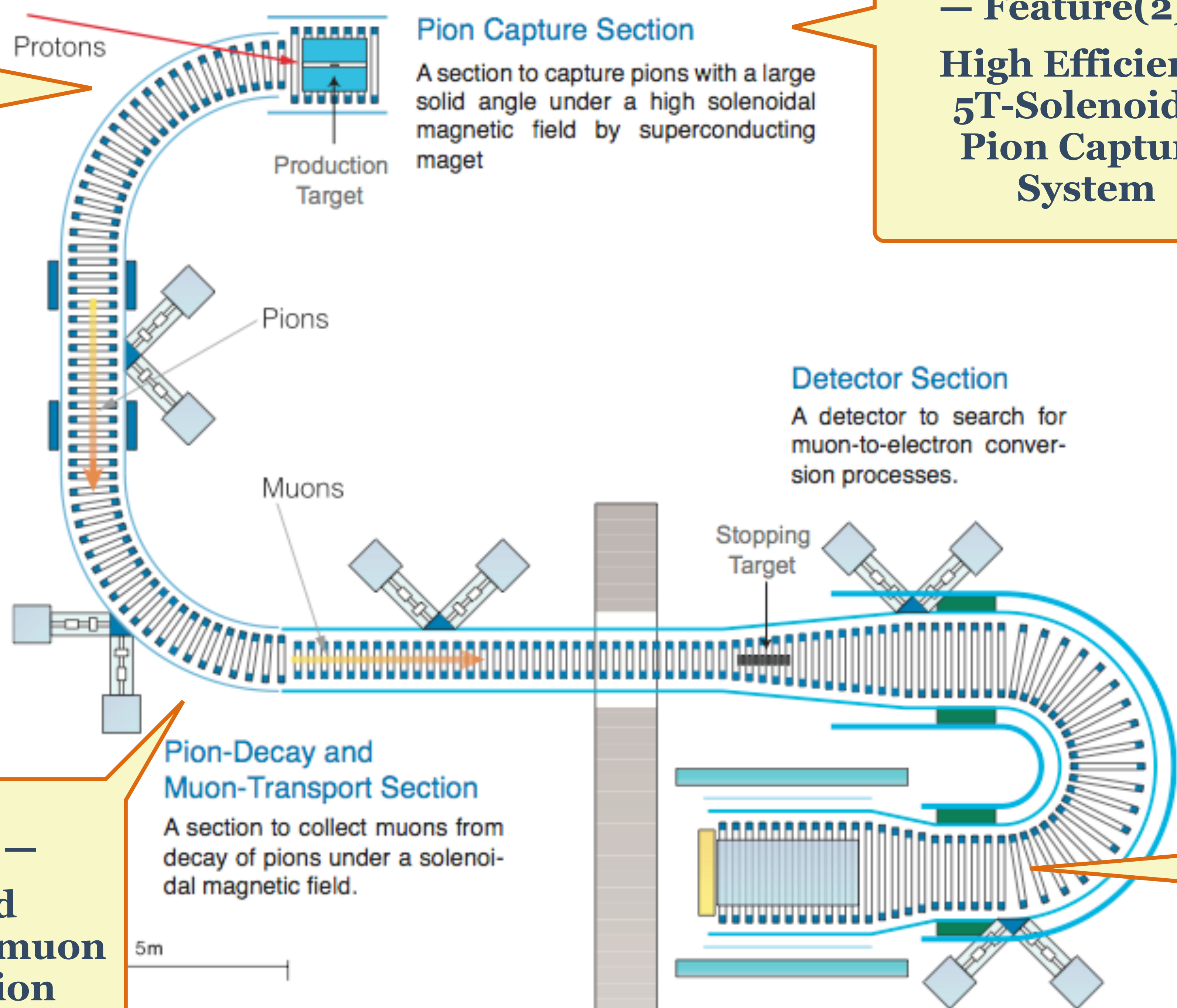
# The COMET Experiment

👉 See C. Carloganu (WG4)

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

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

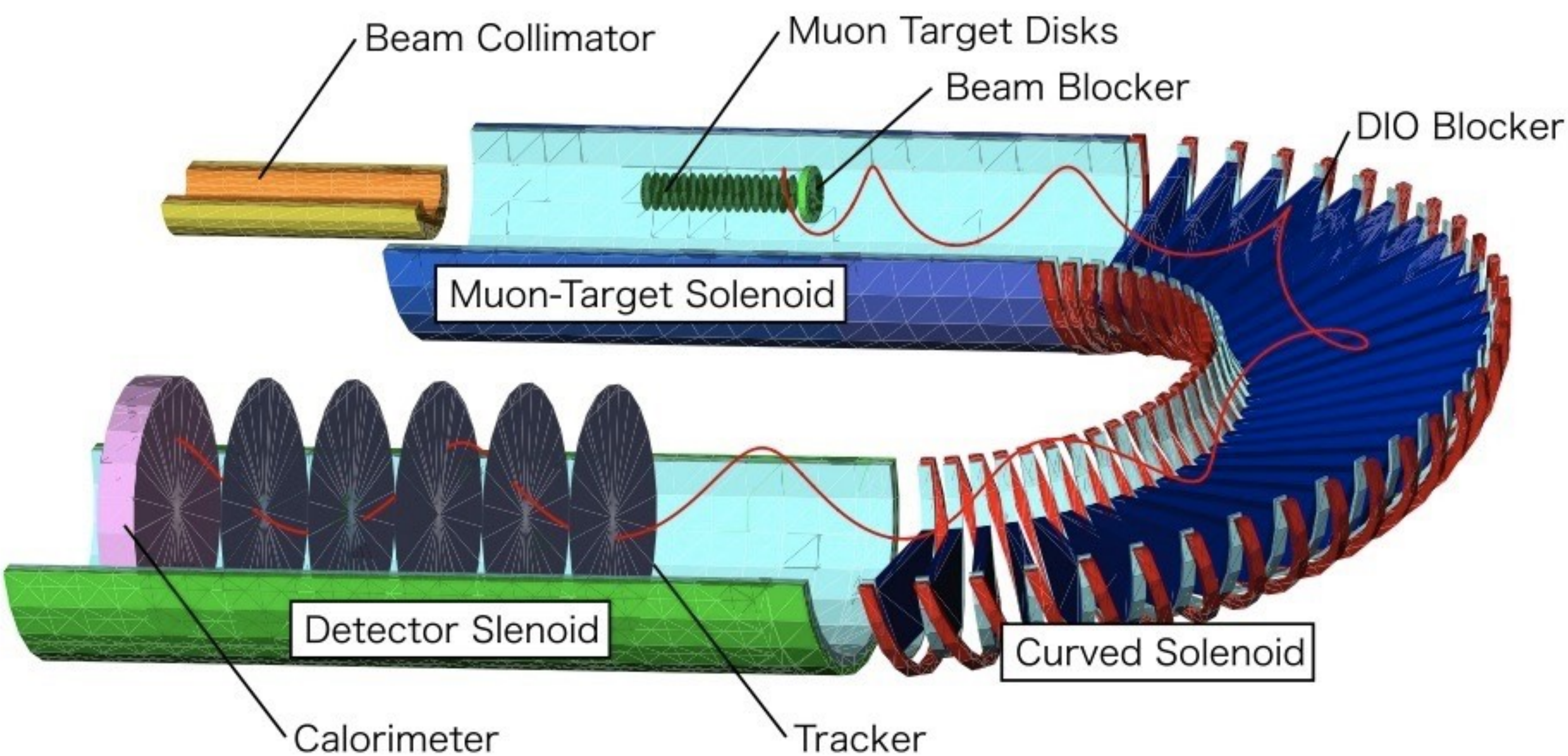
**— Feature(2) —**
**High Efficiency 5T-Solenoidal Pion Capture System**



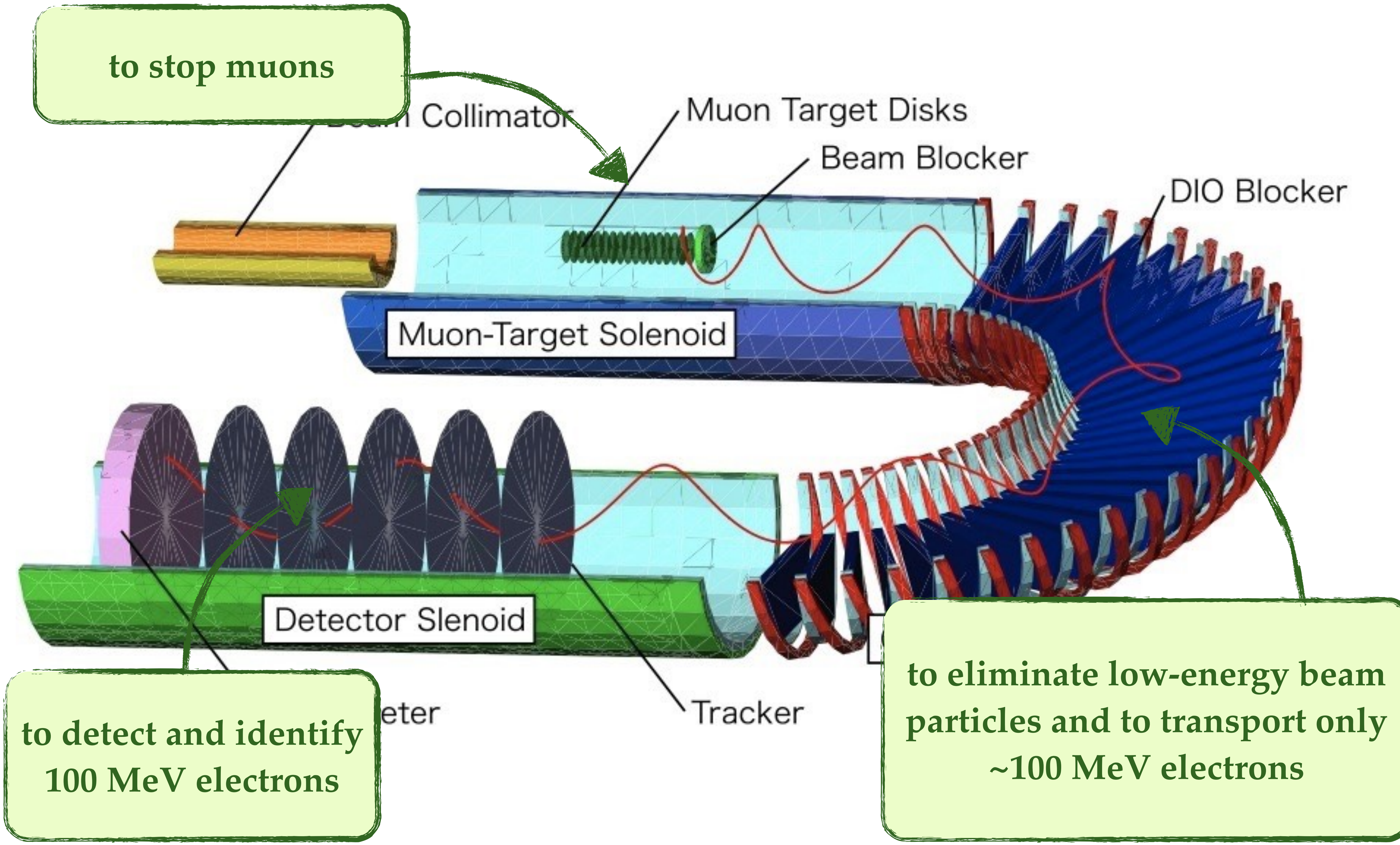

**— Feature(3) —**
**Long/Curved Solenoidal pion/muon transport section**

**— Feature(4) —**
**High resolution, vacuum compatible electron spectrometer can select momentum.**

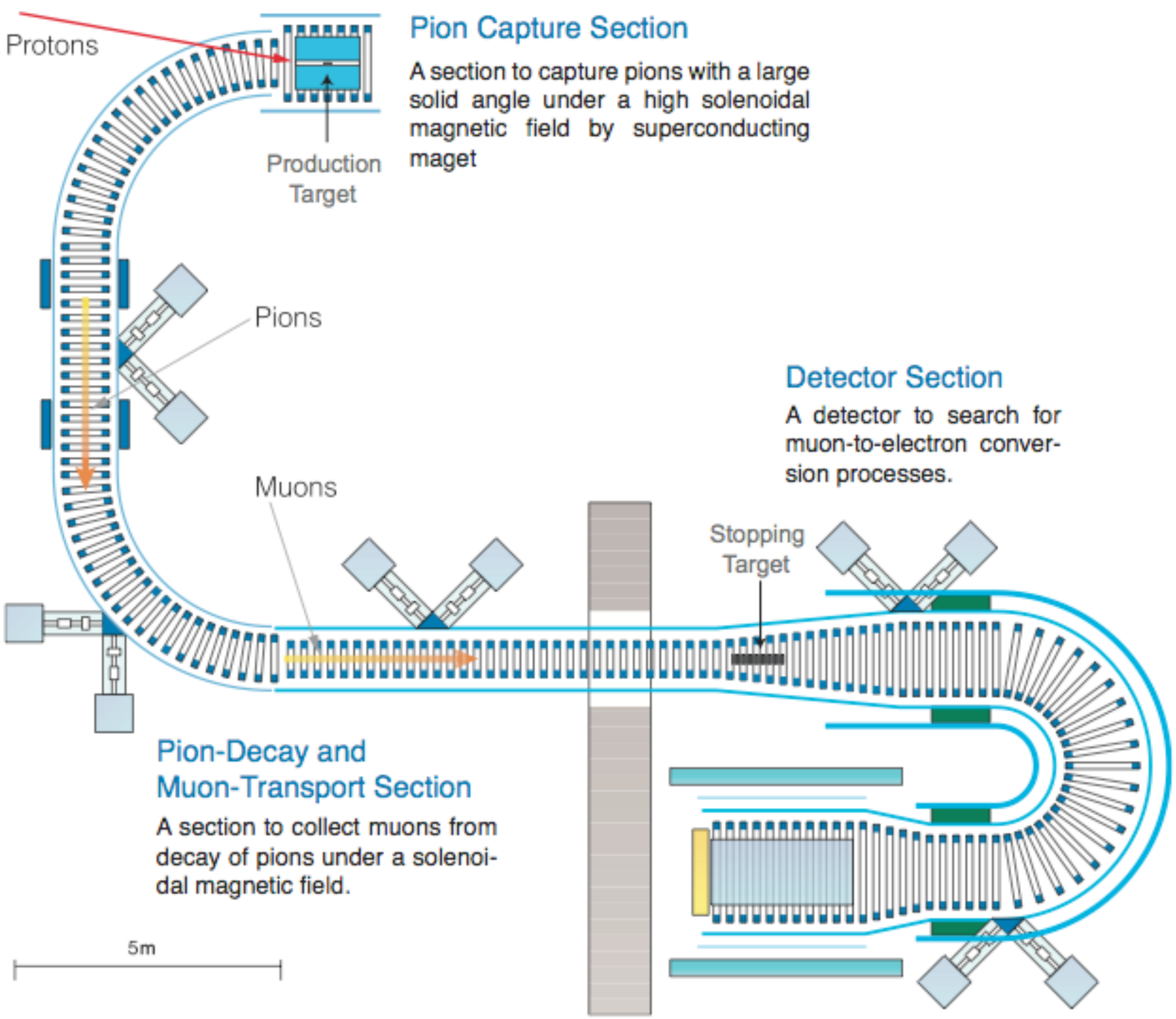
# Detector Apparatus of the COMET



# Detector Apparatus of the COMET



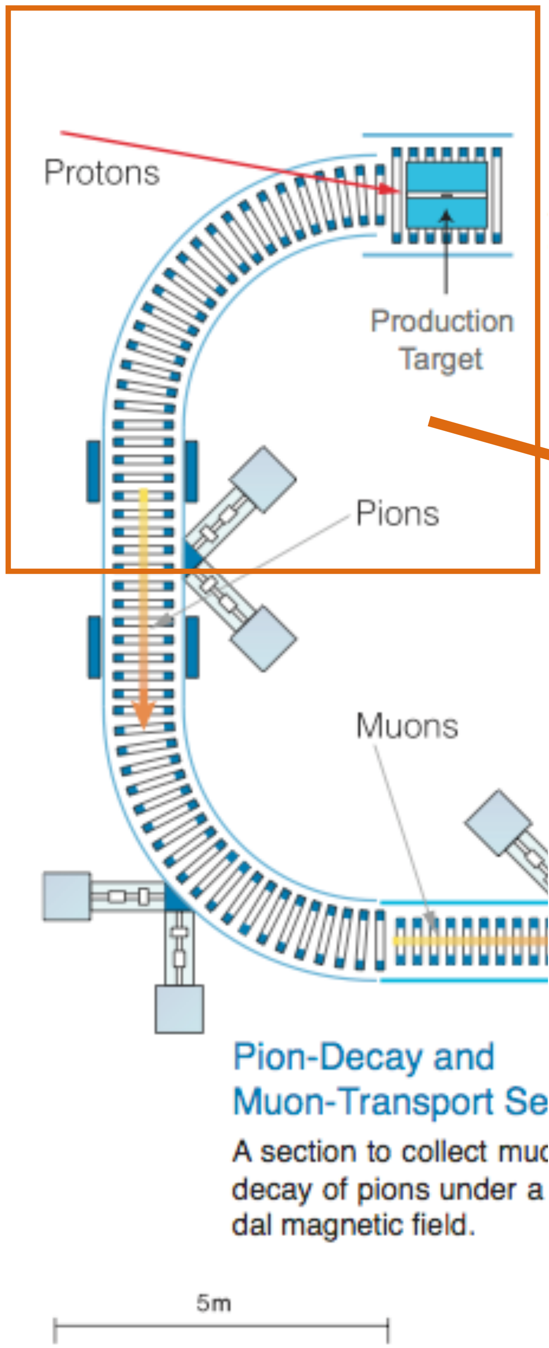
# Dual-Staged Approach

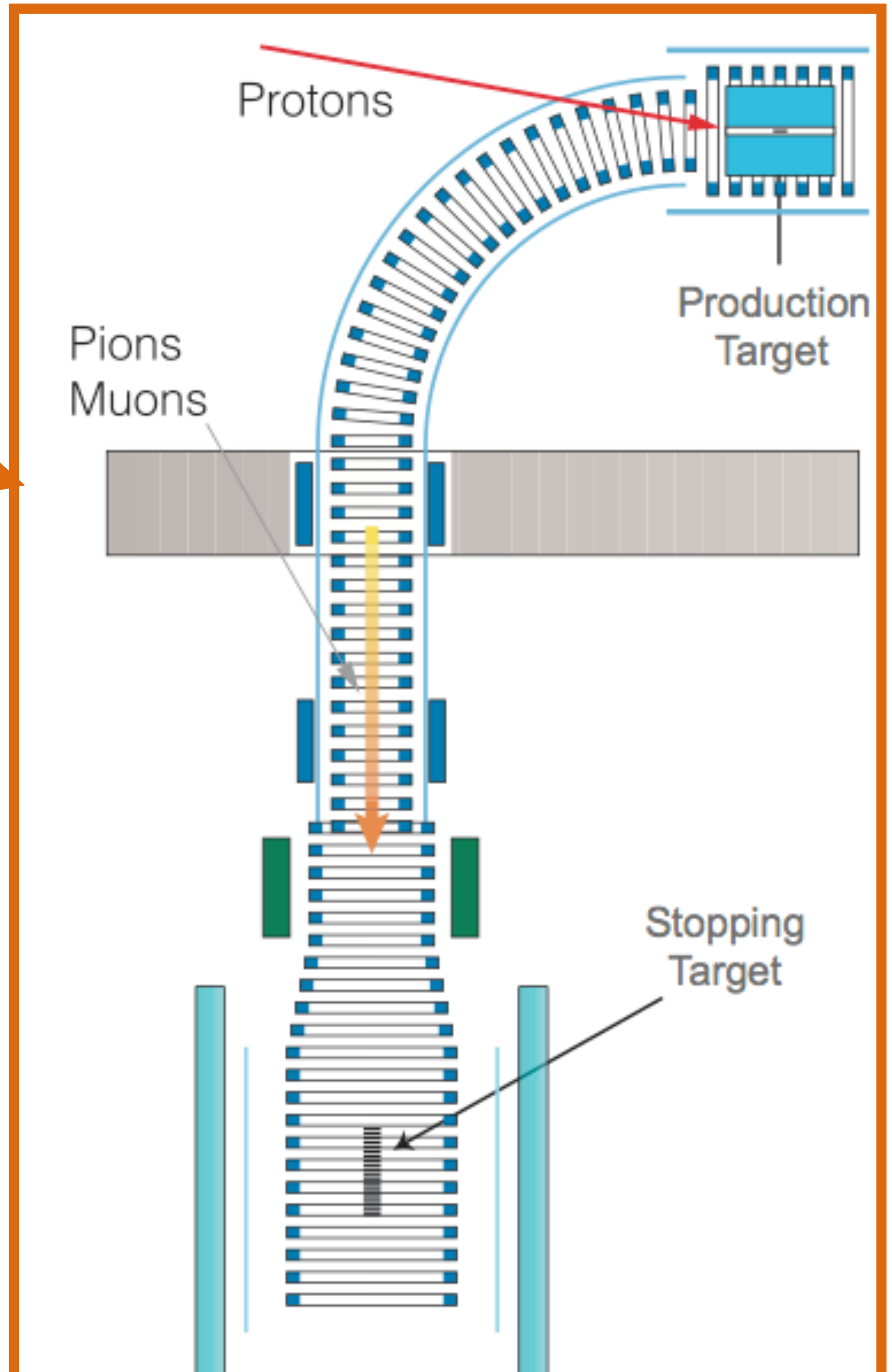



- **COMET Phase-I**
  - Construct up to first 90° bend and place detector.
  - Perform direct beam measurement
    - No backward $\sigma_\pi$ data so far
    - No real BG data so far
  - Perform μ-e Search with an intermediate sensitivity ($O(10^{-15})$)

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

# Dual-Staged Approach

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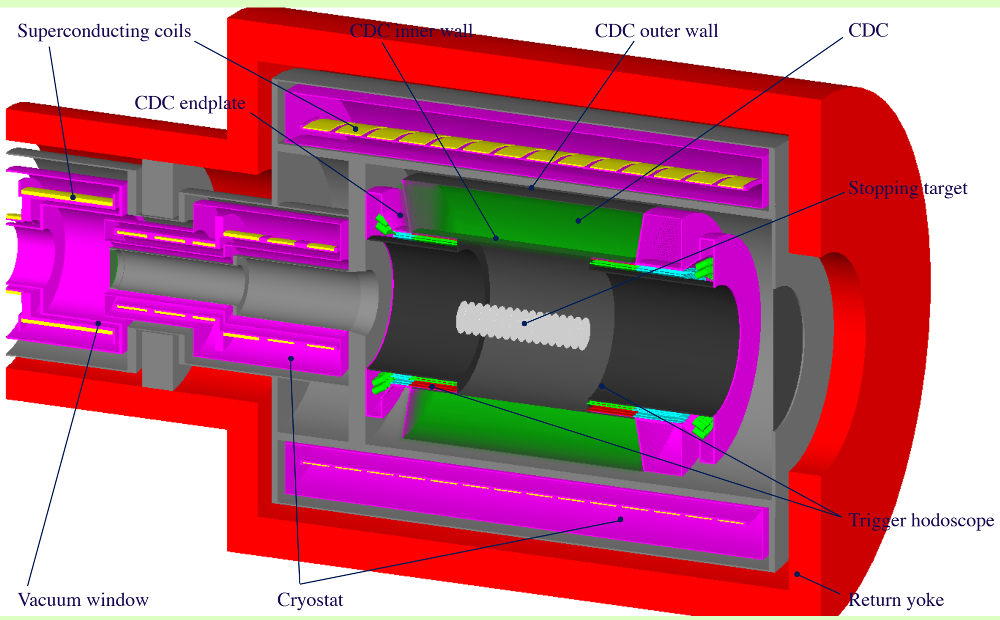
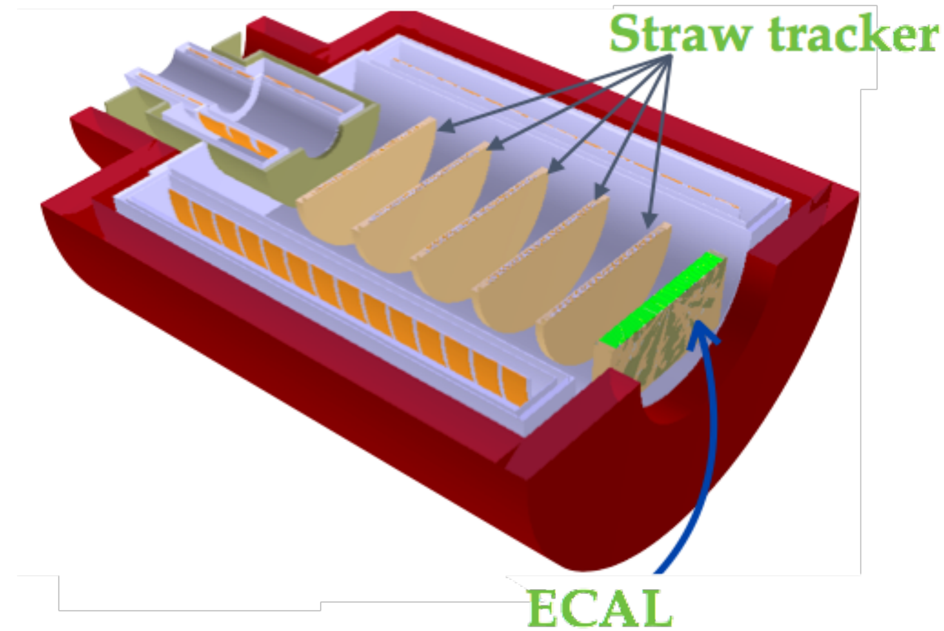
# Detectors for COMET Phase-I

## 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-i$C_4H_{10}$ 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

# The “StrECAL” System

**[ Straw Tracker ]**

**+**

**[ Electromagnetic CALorimeter ]**

# StrECAL : Straw tracker and Electromagnetic Calorimeter

- **For COMET Phase-I, beam detector needs to measure the all delivered beam particle incl. backgrounds;**

To be light material 👉 Vacuum compatible & Thin wall

To have a large acceptance 👉 Planar tracker-based geometry

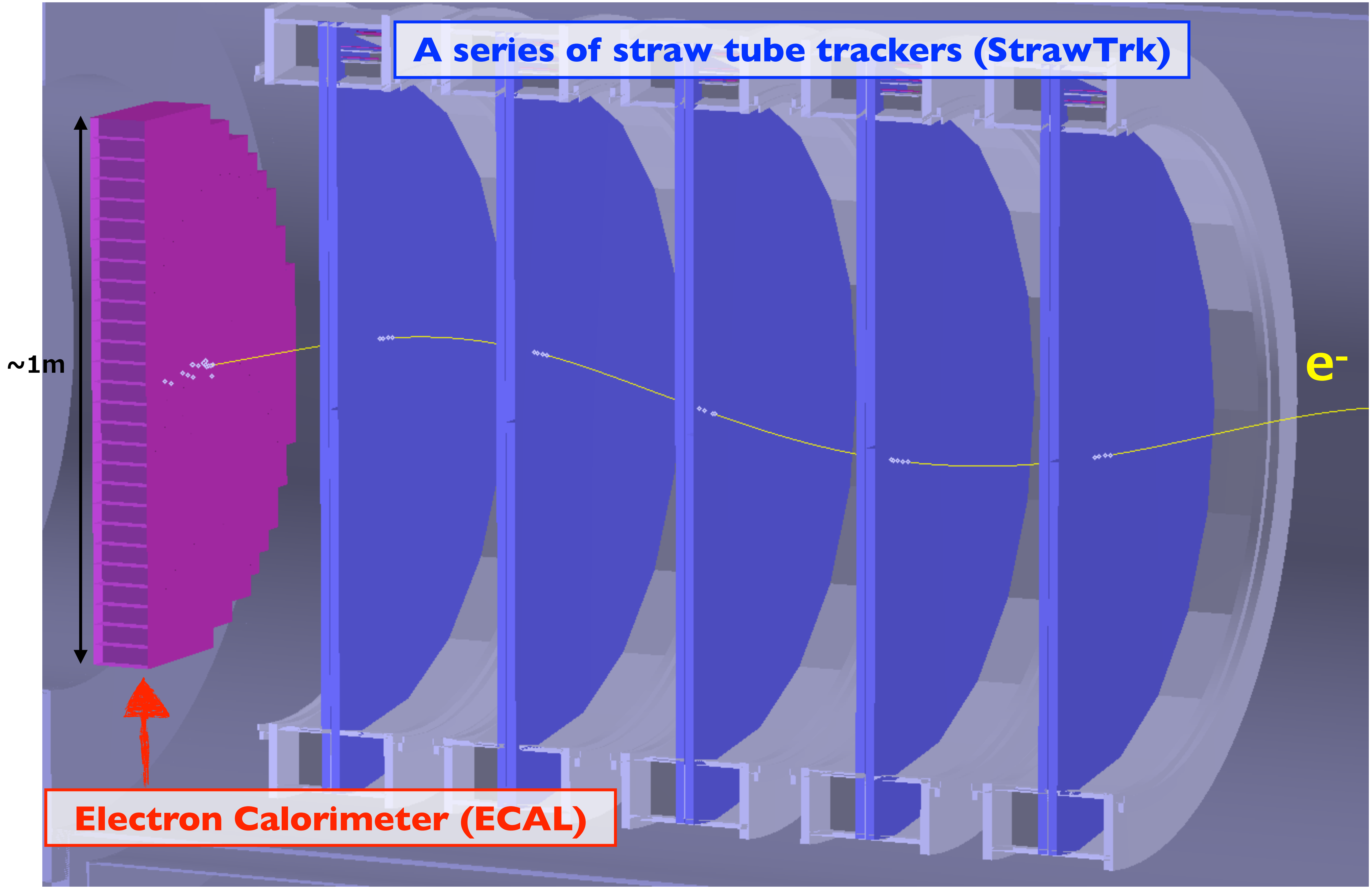
To be capable PID 👉 Long and Heavy enough (TOF & d$E$/d$x$)

To be operational with bunched beam 👉 Finely segmented

↓

# "Straw" + "ECAL" is the BEST

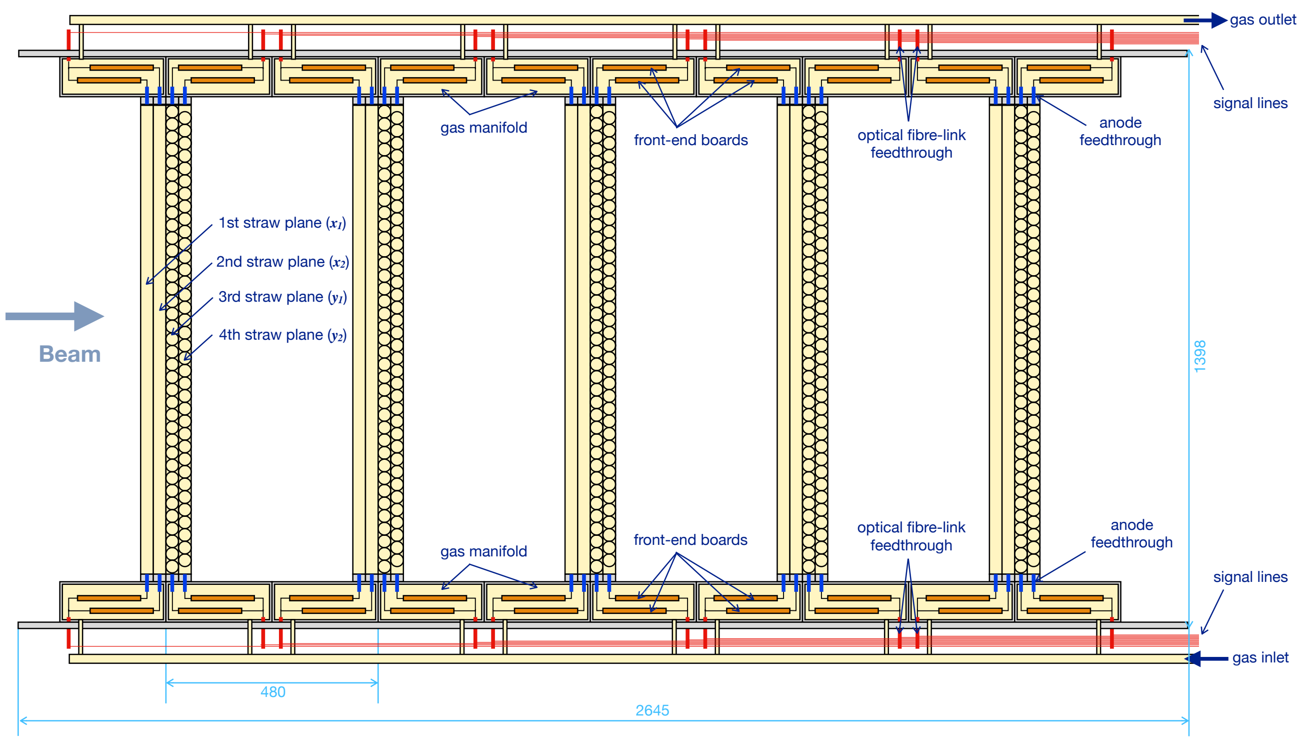
# StrECAL : Straw tracker and Electromagnetic Calorimeter

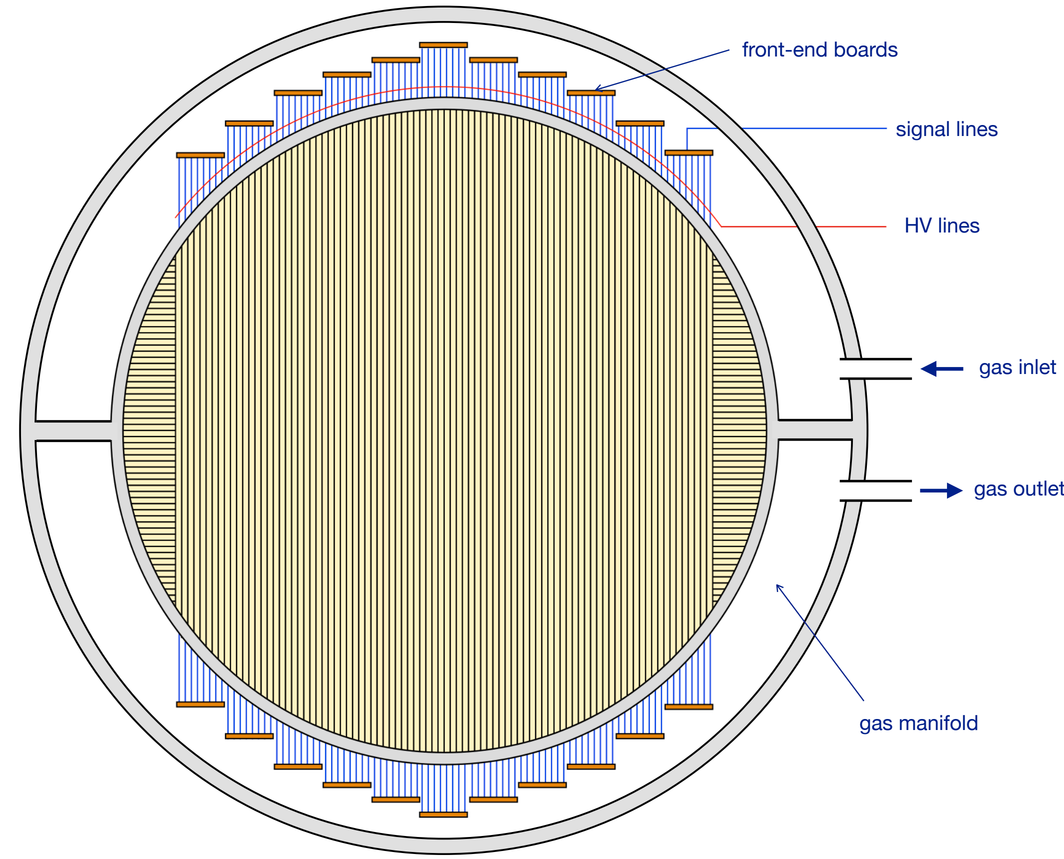


# Straw Tracker (1/5)

👉 See Poster: K.Ueno

- **Planar** wire chamber-based tracker in **Vacuum** → **Straw Tracker**



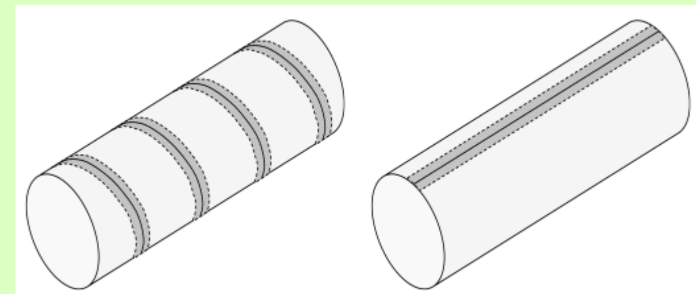

- Five super-layers (station) consist of 4 planes of straw tubes
  - 2 planes for $x$-coordinate and 2 planes for $y$-coordinate, each layer is staggered by half a cell to solve the left-right ambiguity.
- All tracker modules are installed in **vacuum**.
- Timing (Trigger) is provided by the electromagnetic calorimeter.

# Straw Tracker (2/5), Straw Material

- Ultra-thin wall and vacuum tight straw is developed within COMET
  - "$^{t}$20μm-Mylar" + "$^{t}$70nm-Al coat", ϕ9.8mm, enabled by ultrasonic welding

Ultra thin & gas tight is realized by newly developed method (Thanks to NA62 collaboration)

Standard method: "doubly-wound"



newly employed: "straight adhesion"

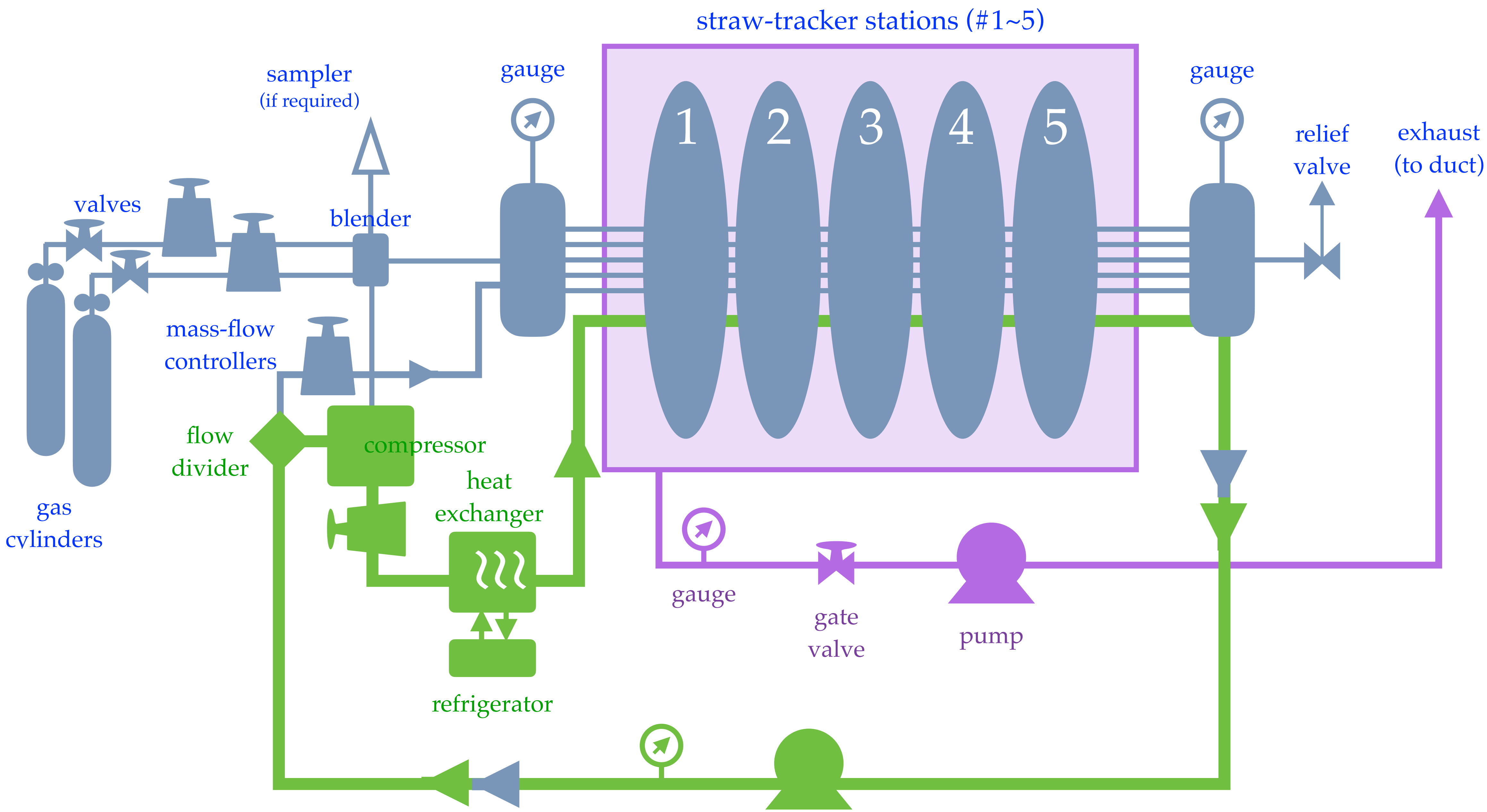
| | NA62 straw | COMET straw 20μm | COMET straw 12μm |
|---|---|---|---|
| Mylar wall thickness | 36 μm | 20 μm | 12 μm |
| Tube diameter | 9.8 mm | 9.8 mm | 5.0 mm |
| Cathode material | Cu(50nm) + Au(20nm) | Al (70 nm) | Al (70 nm) |
| Development status | Currently used in a real experiment | Mass-product Completed, **Detector assemble, ongoing** | **Under R&D** |

**COMET Phase-I** (COMET straw 20μm)

**COMET Phase-II** (COMET straw 12μm)

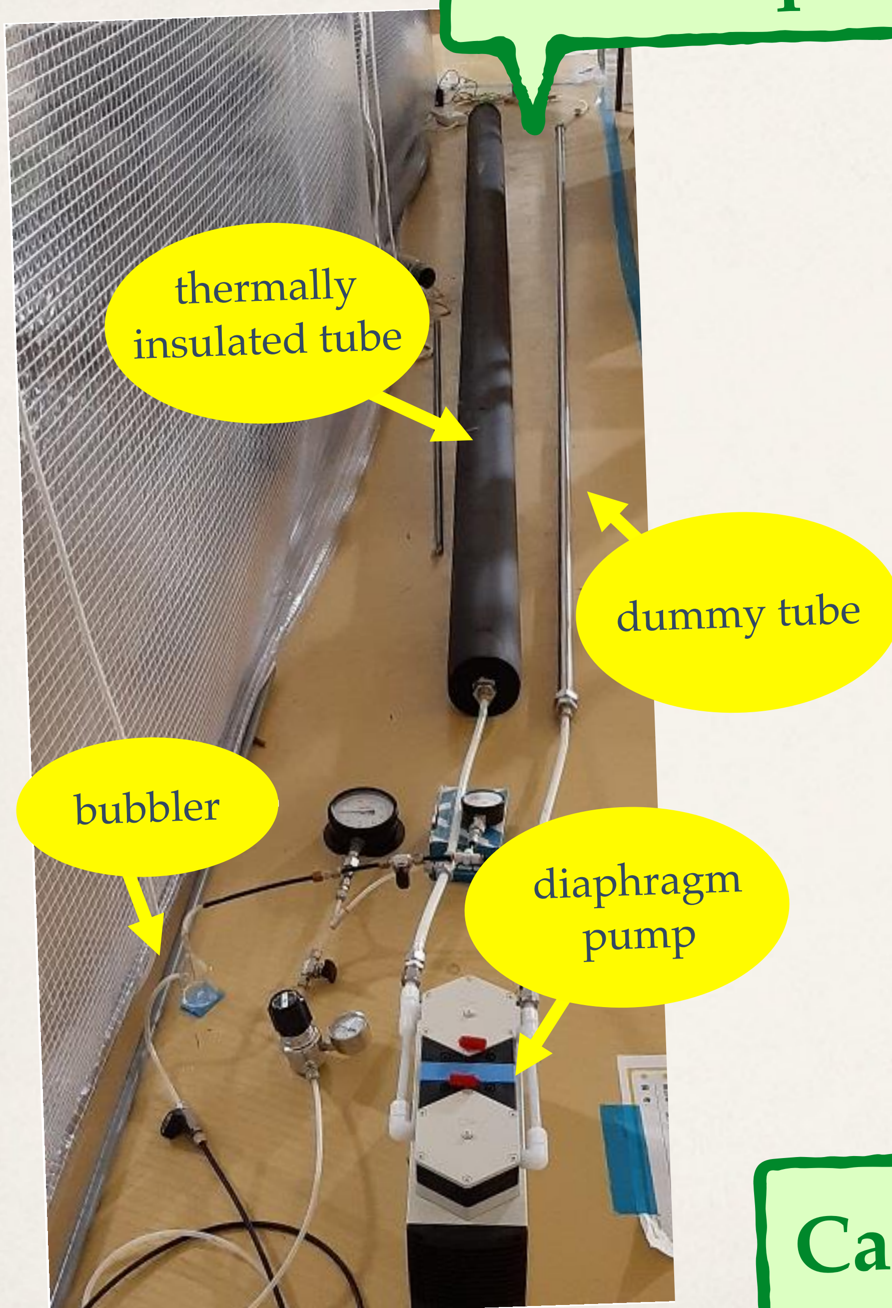
# Straw Tracker (3/5), Gas system

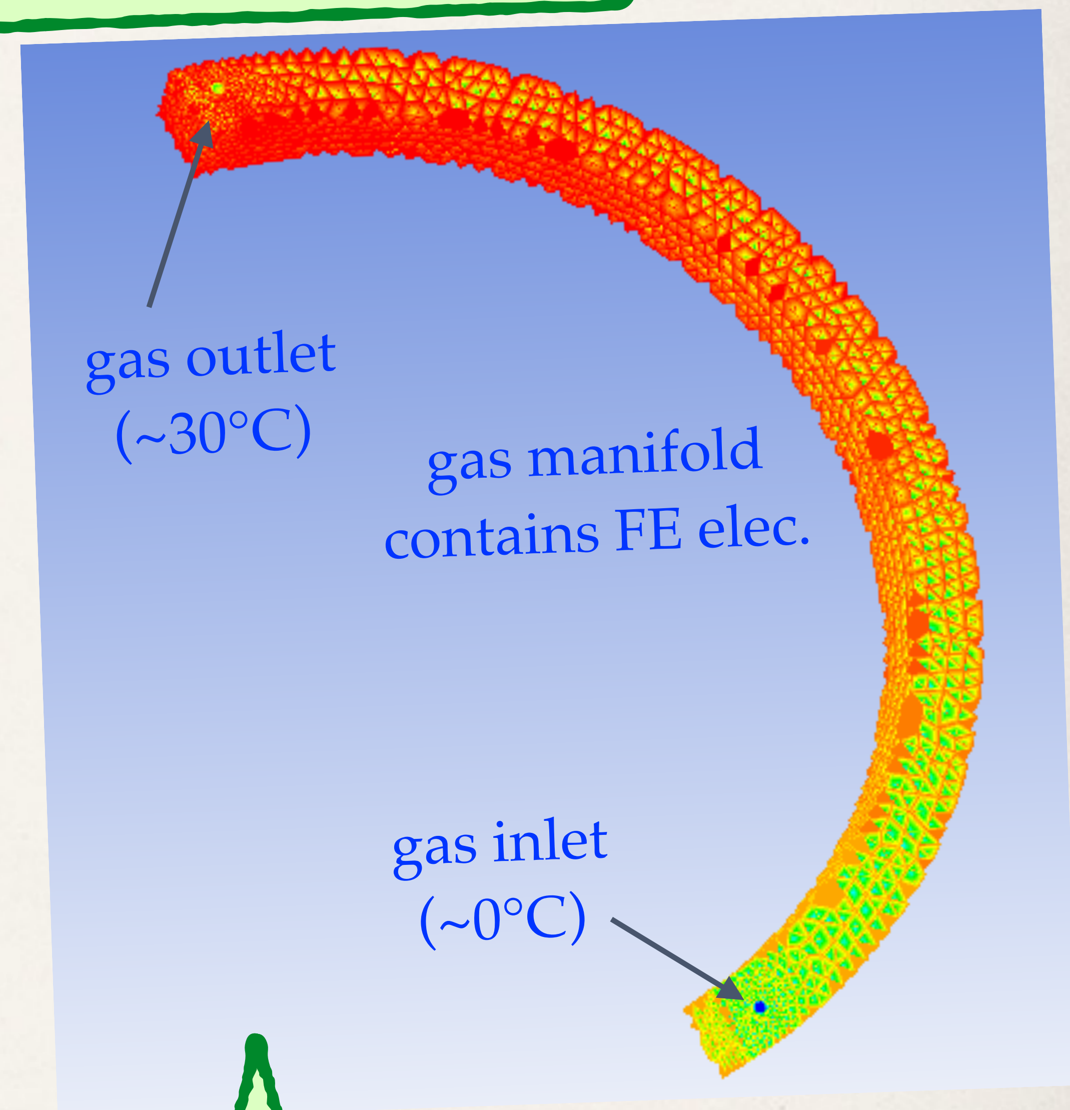
- Chamber gas → Also maintain FE electronics temperature in vacuum vessel
  - Al(50) : $C_2H_6$(50), compressed to make a big flow (~1L/sec) and cooled down to -20°C, → FE electronics would be kept as room temp.



# Straw Tracker (3/5), Gas system

**Pilot test w/o detector satisfice the required specifications**

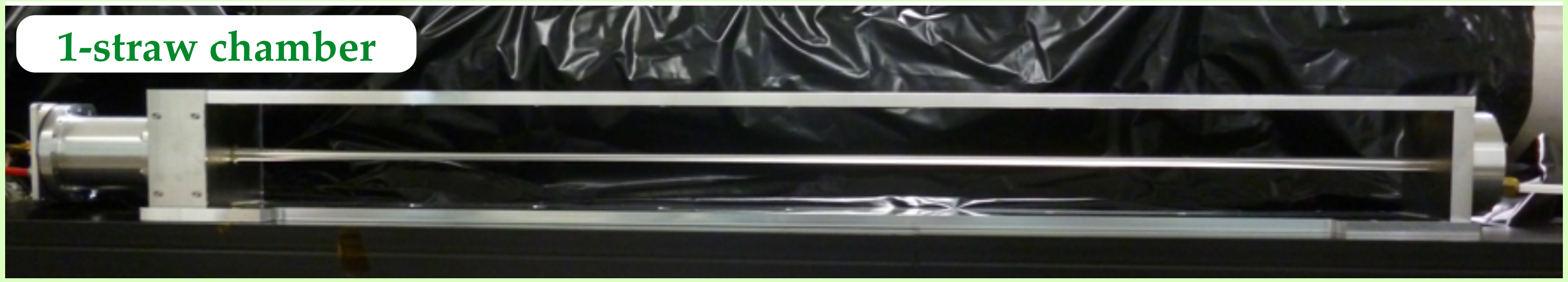


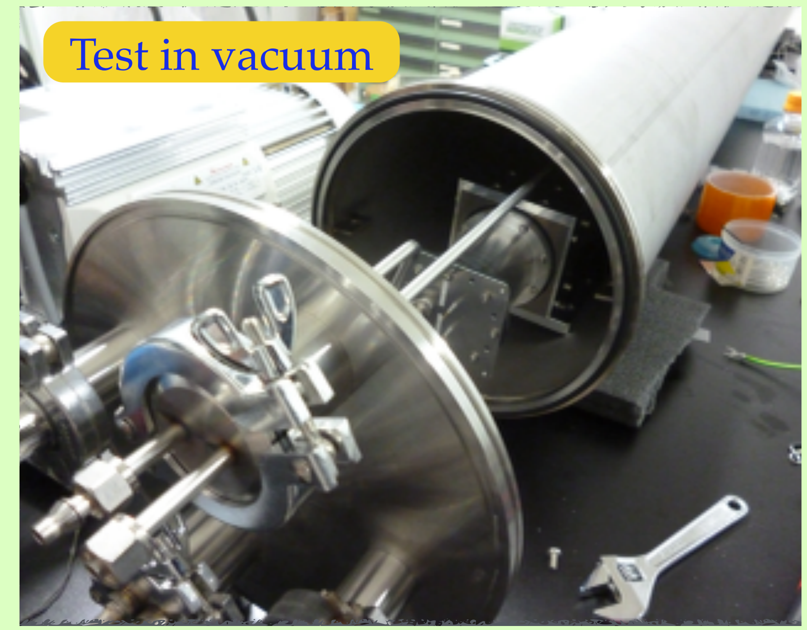

**Calculation (FEM/ANSYS) meets all requirements.**

# Straw Tracker (4/5), Prototyping

- **Prototyping strategy**; 1) 1-straw prototype → 2) Full-scale prototype
  - 1) for assembly technique R&D, 2) for performance validation

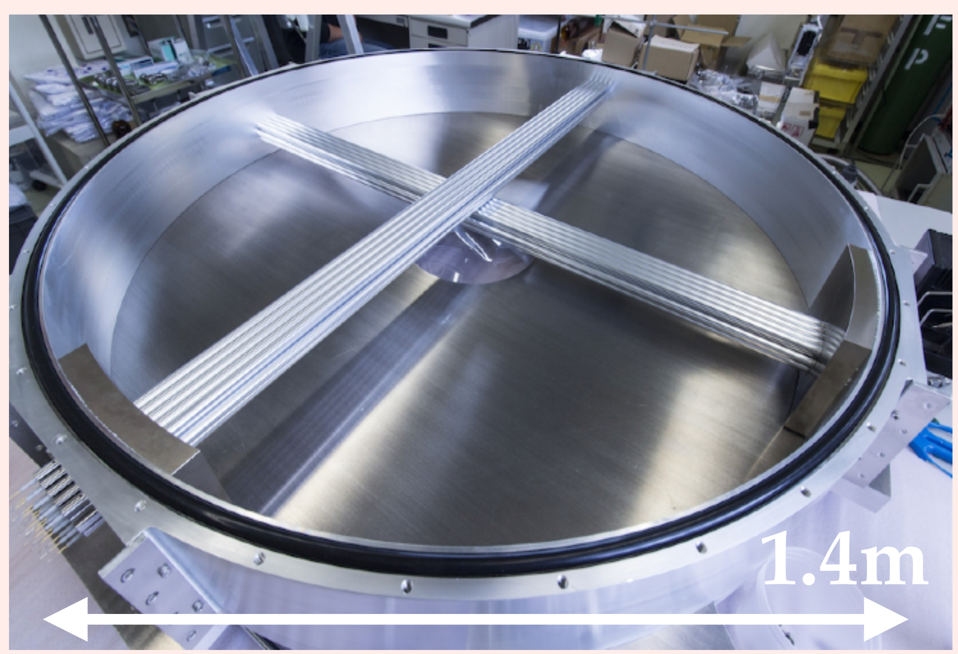



- Basic assemble technique was established, *eg*. pre-tension, feedthrough, gas tightness, *etc*.
- Vacuum compatibility was also confirmed, *eg*. outgas, leak, pressure maintenance, *etc*.



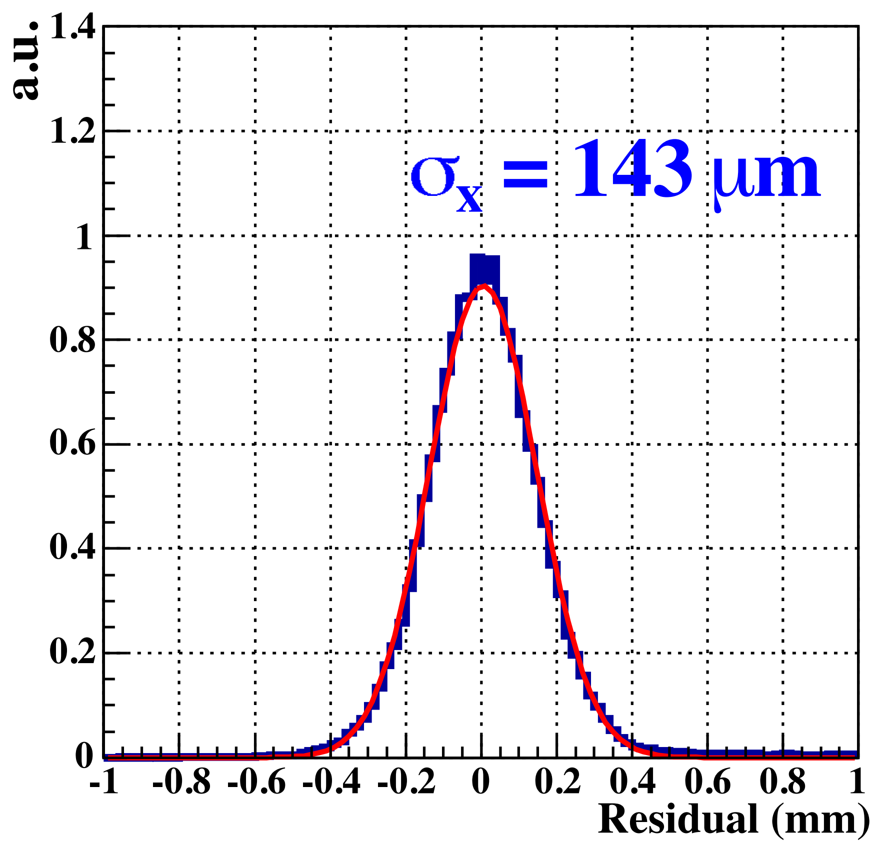

**Full-Scale Prototype**

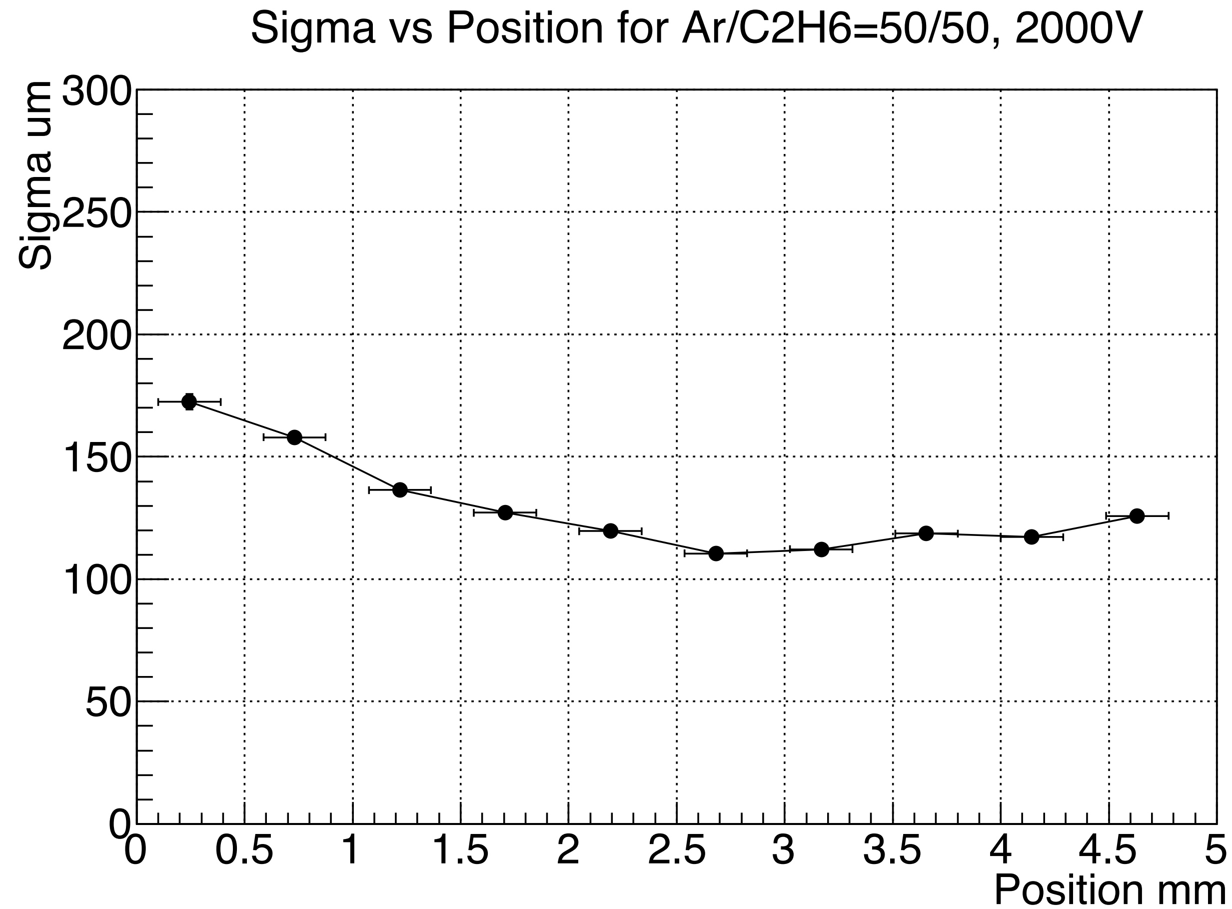
- All parameters, *eg*. size, electronics, gas, *etc*., are same as final detector, but only # of straw is small → Only 32 straws (16 for x-axis, 16 for y-axis) are installed.




- Detector performances, *eg*. efficiency, resolution, stability, vacuum compatibility, *etc*., are investigated with a 105 MeV / *c* electron beam and final experimental conditions.

# Straw Tracker (5/5), Detector Performance

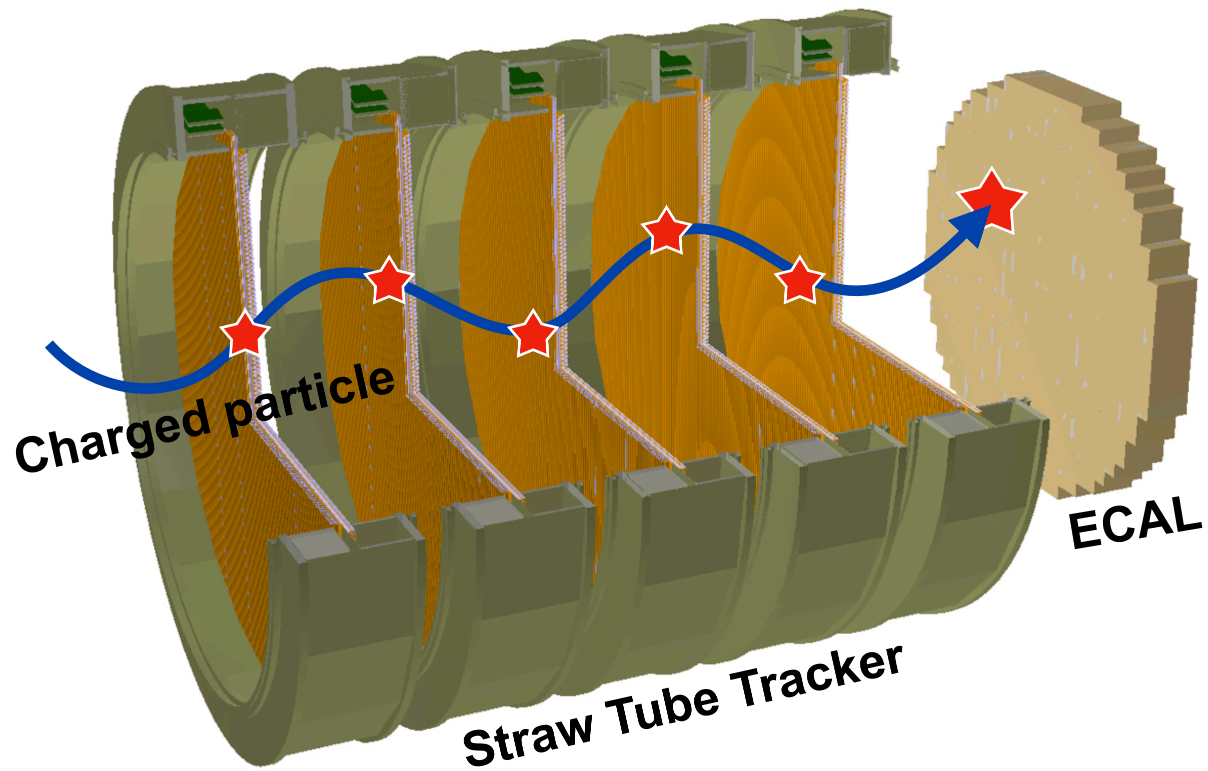



- Test-beam w/ 105 MeV/c electron was conducted at Tohoku university.
- Vacuum tightness has been proven down to 0.1 Pa
- Spatial resolution better than 150μm has been confirmed
  - Good enough to realize a required momentum resolution of <200keV/*c* with a 1T magnetic field)
- Detector design has been fixed based on these studies by Full-scale prototype
  👉 Green signal to start construction of Phase-I straw tracker

# ECAL (1/4), Electromagnetic CALorimeter

- **Purposes**;
  1) Measure electron energy with a good resolution
  2) Provide hit position with electron trajectory at the ECAL position
  3) Provide the trigger and the timing information




- **Requirements**;
  - Energy resolution;
    - $\sigma_E < 5\%$ @ 105 MeV
  - Cluster position resolution;
    - $\sigma_x < 1$ cm
  - Fast timing response
    - $f_t < 100$ nsec
  - Operational in B-field (1T)

- **Solutions**;
  - Highly segmented scintillating crystals with high light yield and fast response
    - LYSO
  - Silicon-based photodiode & low-noise preamplifier
    - APD (Avalanche photodiode)

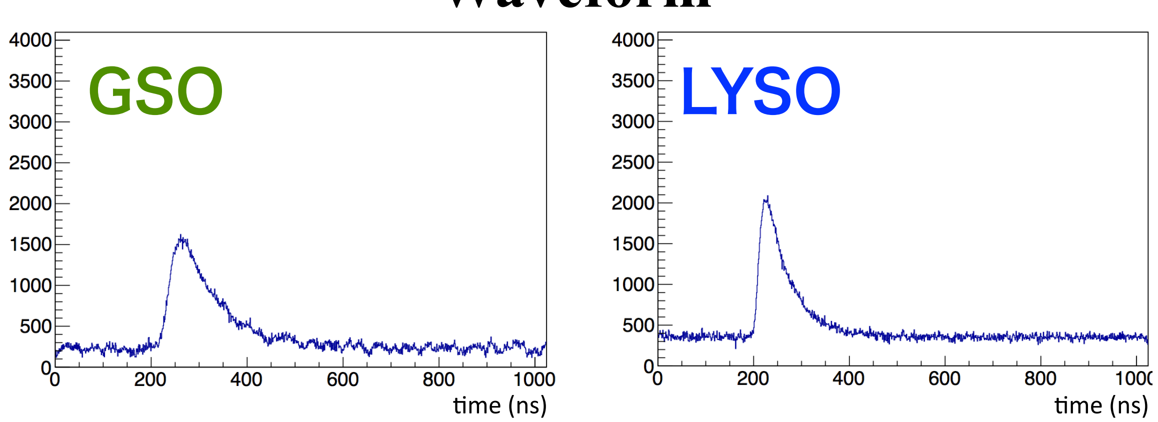
# ECAL (2/4), LYSO Crystal

- **R&D in the collaboration**
  - Choice of the candidate crystals
    - GSO: 20x20x150mm³ ($10.9X_0$)
    - LYSO: 20x20x120mm² ($10.5X_0$)

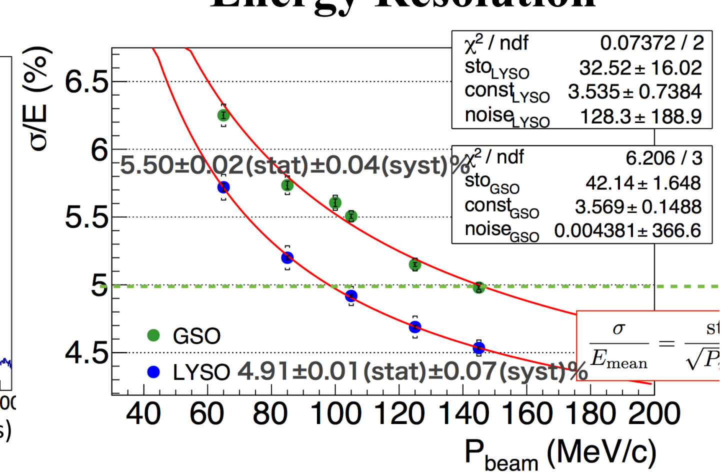
| | GSO(Ce) | LYSO | PWO | CsI(pure) |
|---|---|---|---|---|
| Density (g/cm$^3$) | 6.71 | 7.40 | 8.3 | 4.51 |
| Radiation length (cm) | 1.38 | 1.14 | 0.89 | 1.86 |
| Moliere radius (cm) | 2.23 | 2.07 | 2.00 | 3.57 |
| Decay constant (ns) | $600^s$, $56^f$ | 40 | $30^s$, $10^f$ | $35^s$,$6^f$ |
| Wave length (nm) | 430 | 420 | $425^s$, $420^f$ | $420^s$, $310^f$ |
| Refractive index at peak emission | 1.85 | 1.82 | 2.20 | 1.95 |
| Light yield (NaI(Tl)=100) | $3^s$, $30^f$ | 83 | $0.083^s$, $0.29^f$ | $3.6^s$,$1.1^f$ |

- **Performance-cost evaluation**
  - Test-beam experiment has been carried out to decide the choice
    - With 5x5mm² APDs, 1st prototype preamp, and 105 MeV / $c$ electron
  - Our decision from the results is **LYSO**

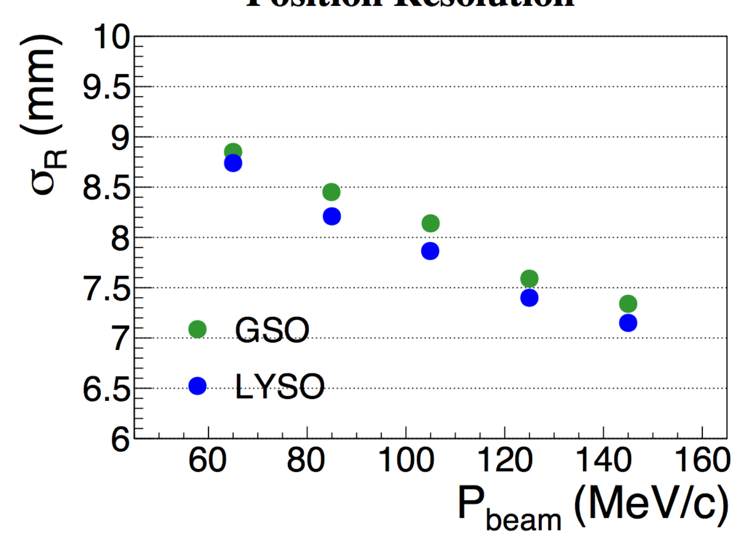
**Waveform**




**Energy Resolution**

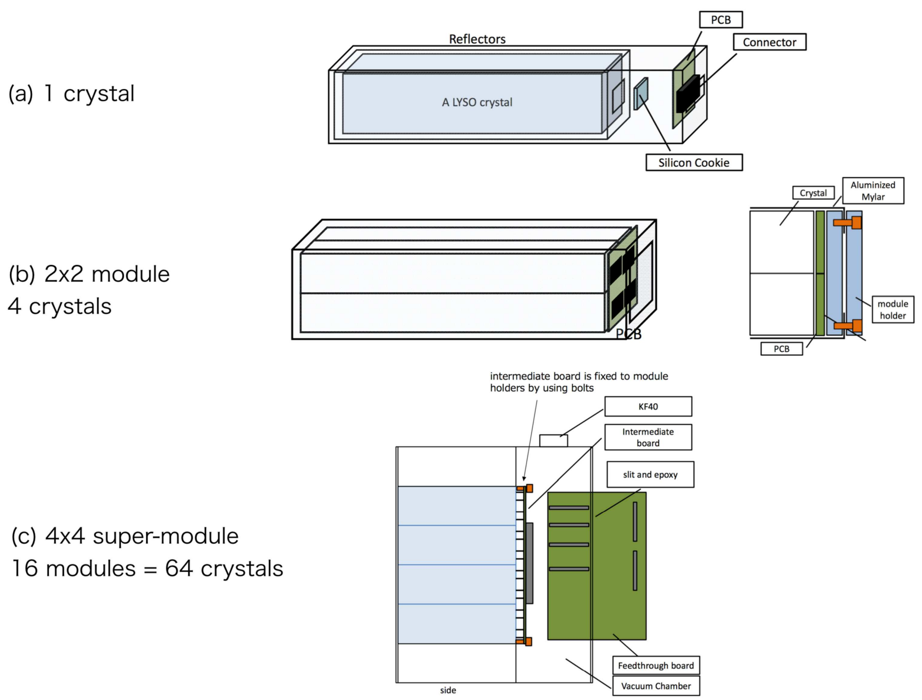


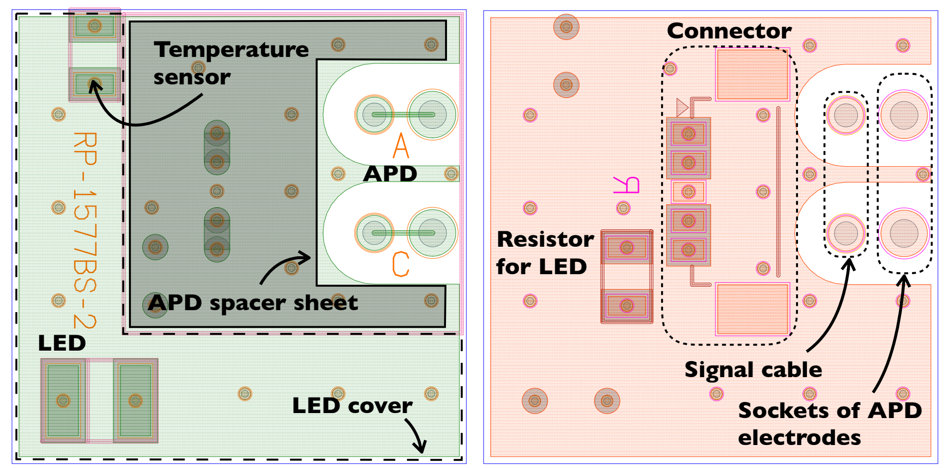

**Position Resolution**



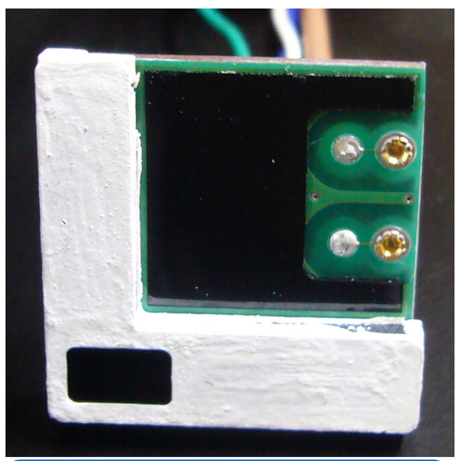
# ECAL (3/4), Assembly

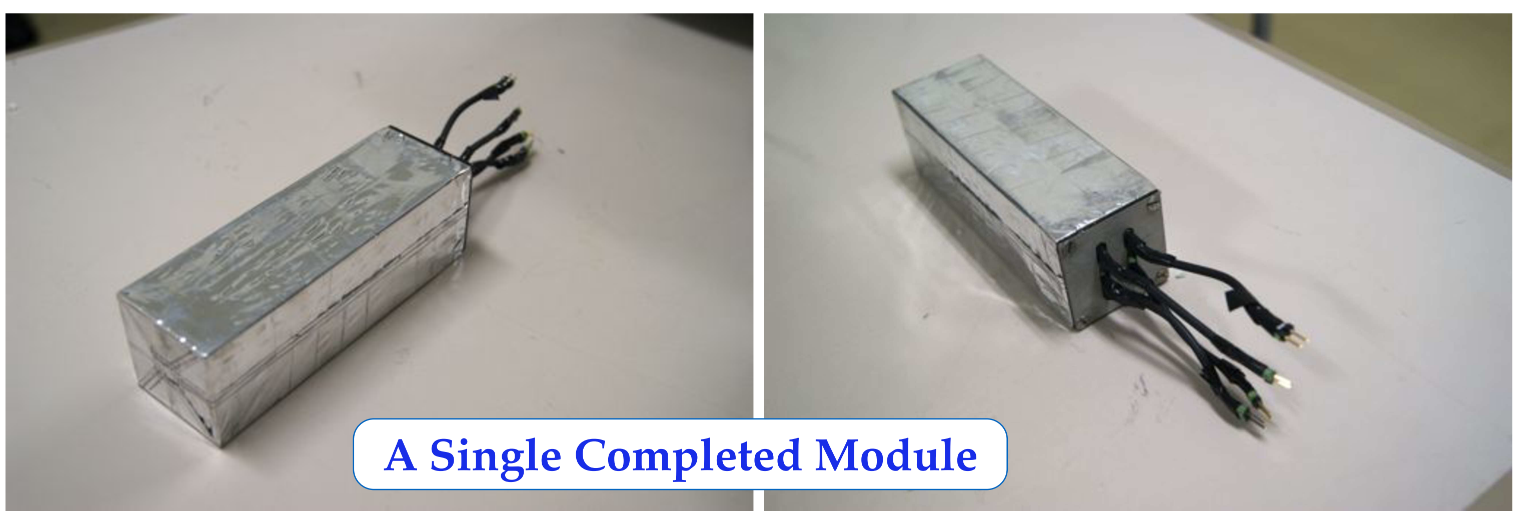
- Module-base assembly is employed
  - Basic unit = 2x2 crystal matrix module
  - × 480 modules to cover the full cross-section of detector fiducial

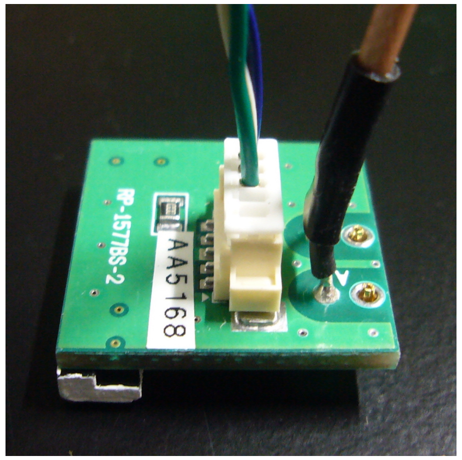


Front (Crystal side)
Back (Cabled side)


Front view w/o APD


A Single Completed Module

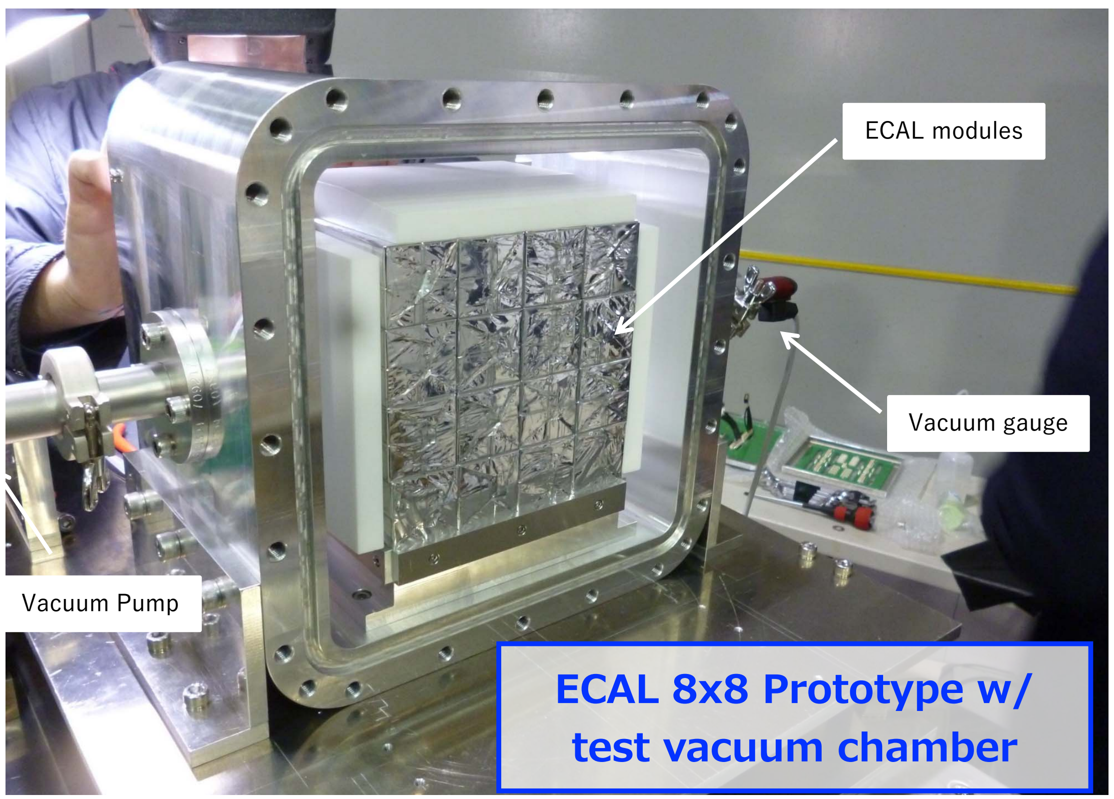


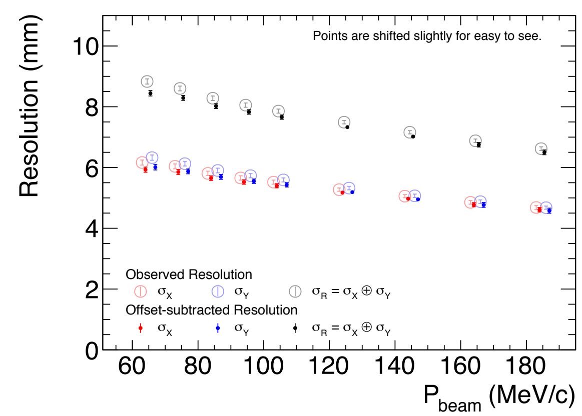
Back view


2x2 APD board

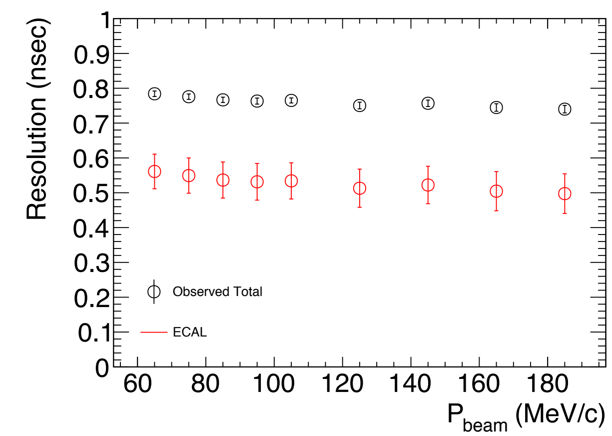
# ECAL (4/4), Prototype

- Last prototype (with the final matrix configuration but only 16 modules, LYSO size, APD, FE-electronics, signal feedthrough) was constructed.
  - Test-beam experiment with 105 MeV / $c$ electron was conducted

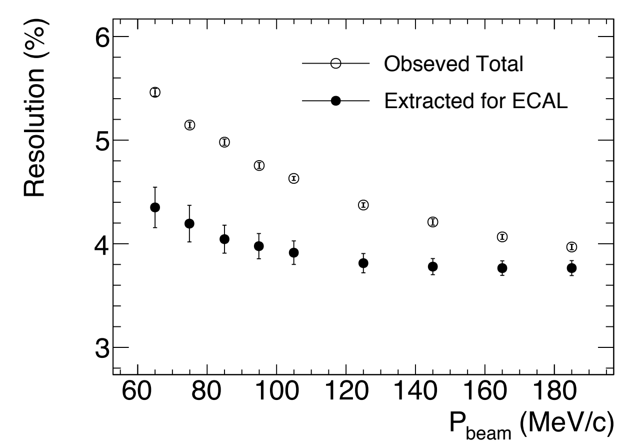



$\sigma_x$




$\sigma_t$



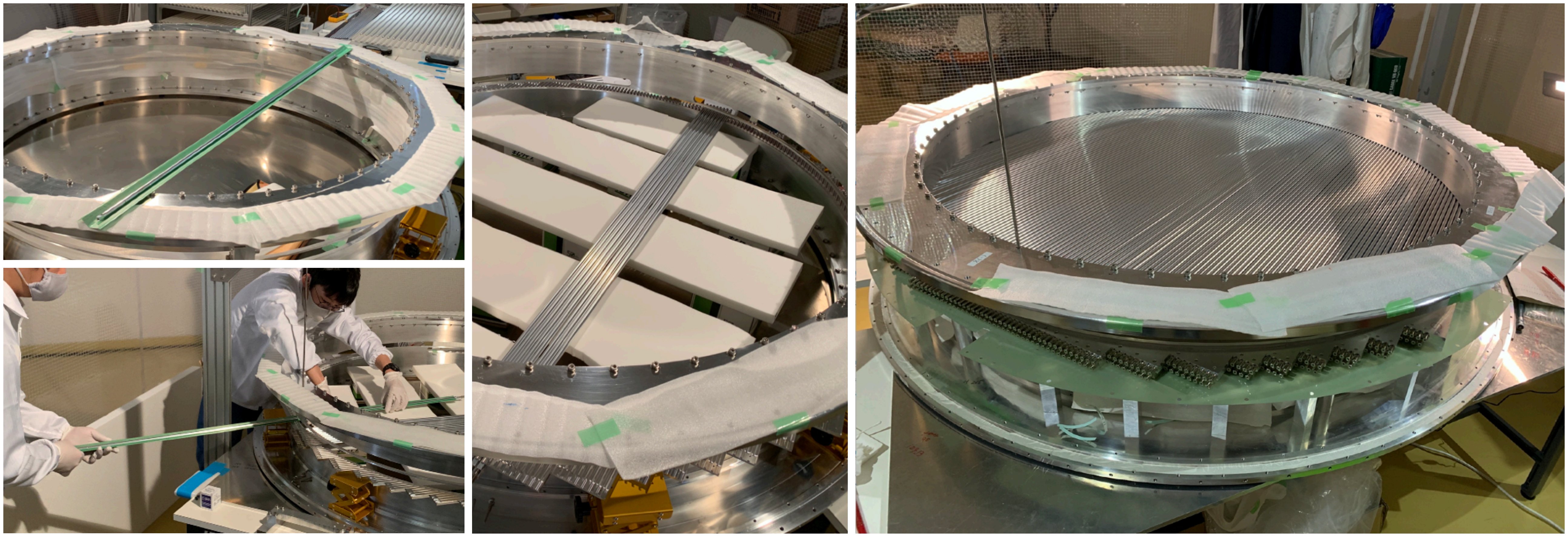

$\sigma_E$

- Prototype was successfully operated in vacuum
- Excellent performances that satisfies requirements for COMET Phase-I & II
  - $\sigma_E/E = 4\%$, $\sigma_x < 6\text{mm}$, $\sigma_t = 0.5$ nsec @ 105 MeV electron beam
  - Scalable to the actual detector 👉 Final design for Phase-I has been fixed.

# Current Status

# Straw Tracker Assembly for Phase-I

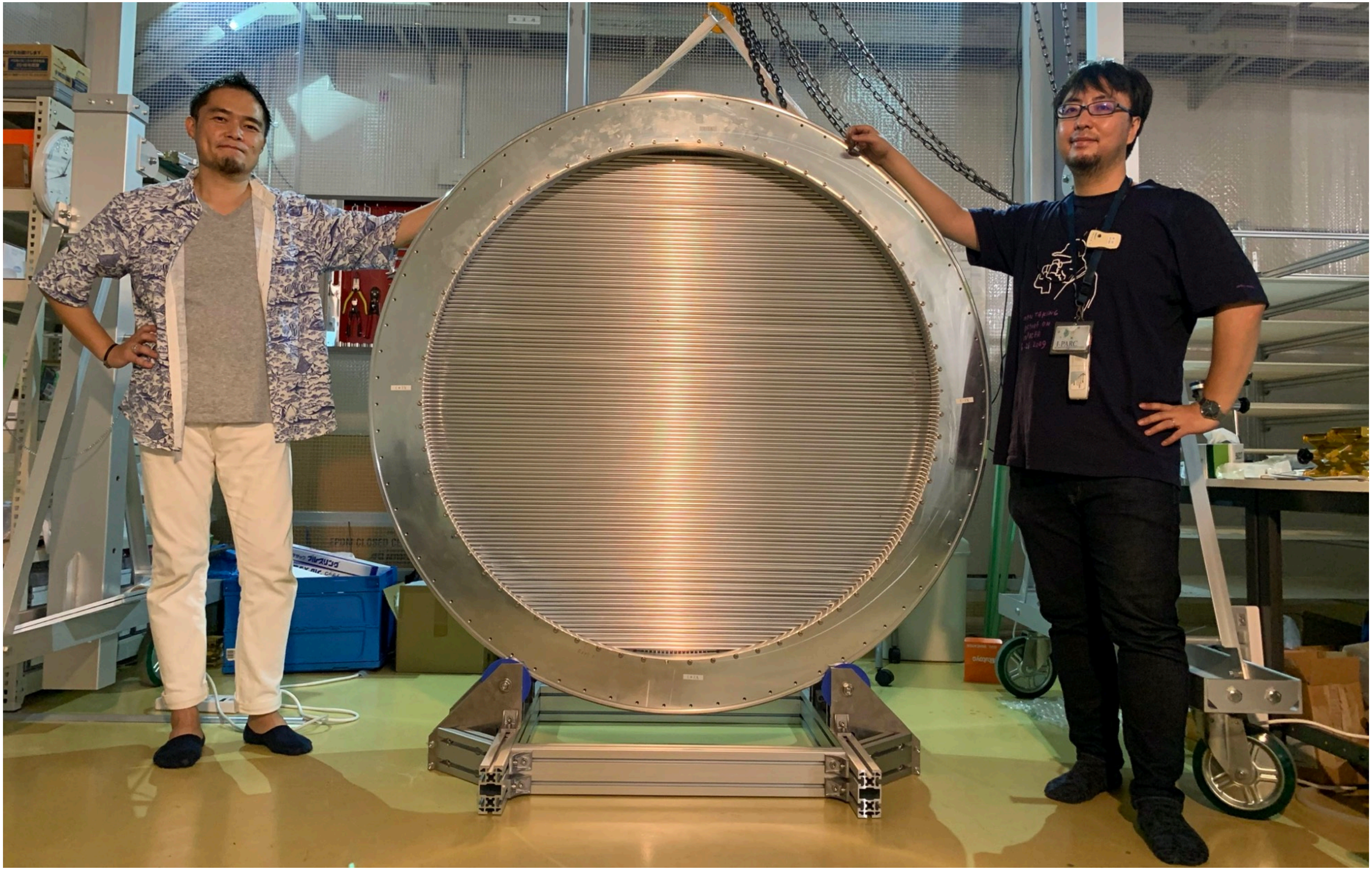
- Straw assembly with a support structure (pressure vessel) performed (**Station #1**)



- Started in 2020, All steps; 1) glueing with end-plug of straw, 2) fixing the straw-positioning jig, 3) straw insertion, 4) applying the tension on all straws (1.3 $kg_f$), and 5) glueing all ends of straws, are finished.

**All straws for Station #1 (4 planes, 480 tubes in total) installation, completed !!**

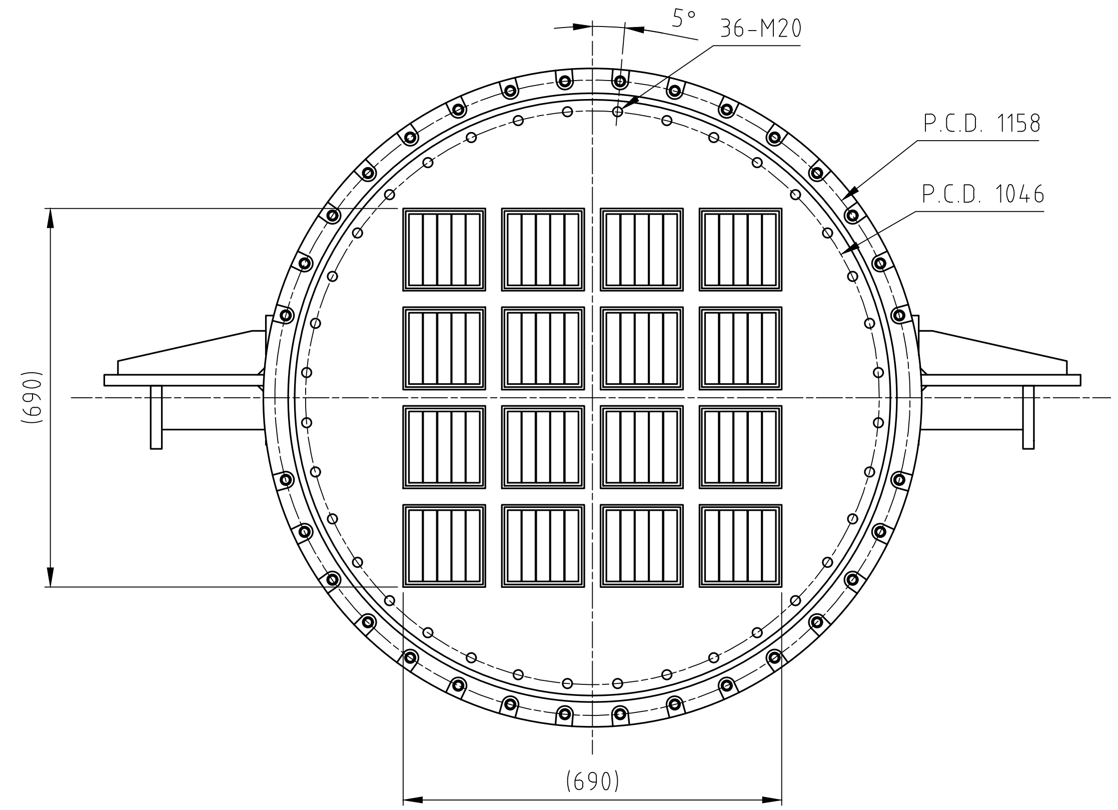
# Completed Straw Station #1

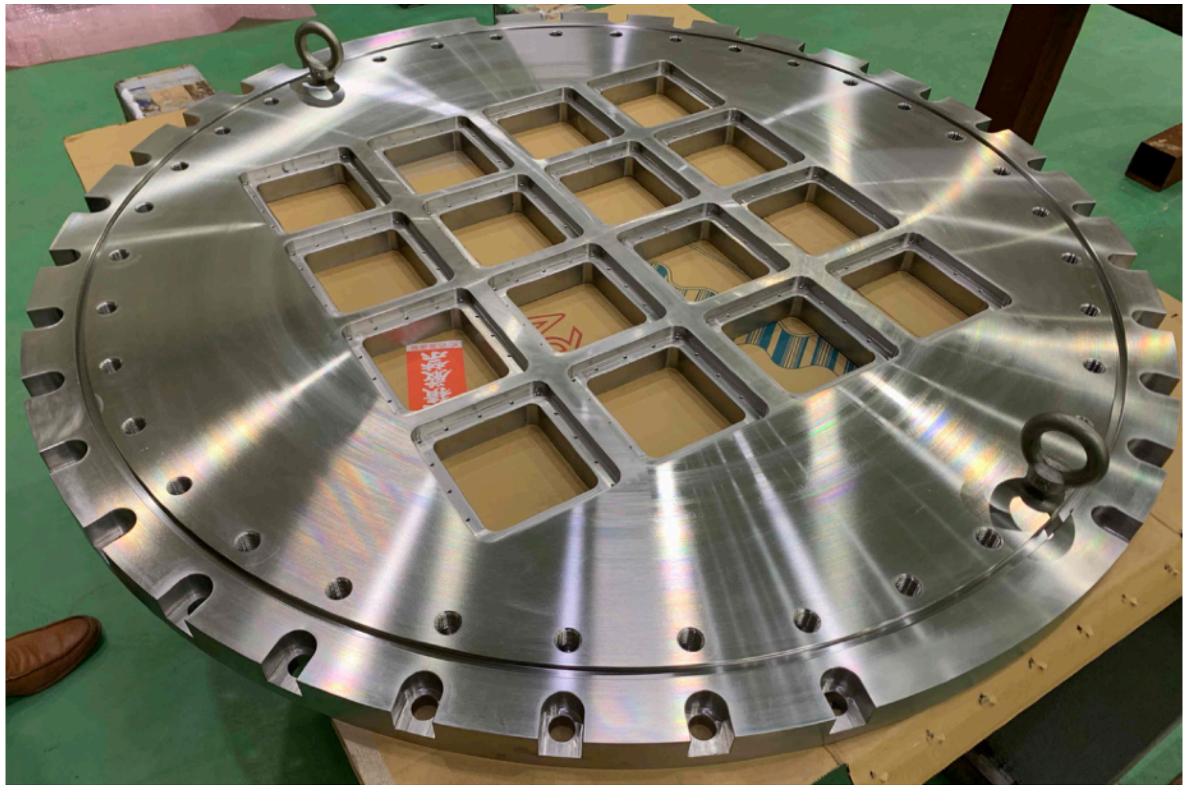


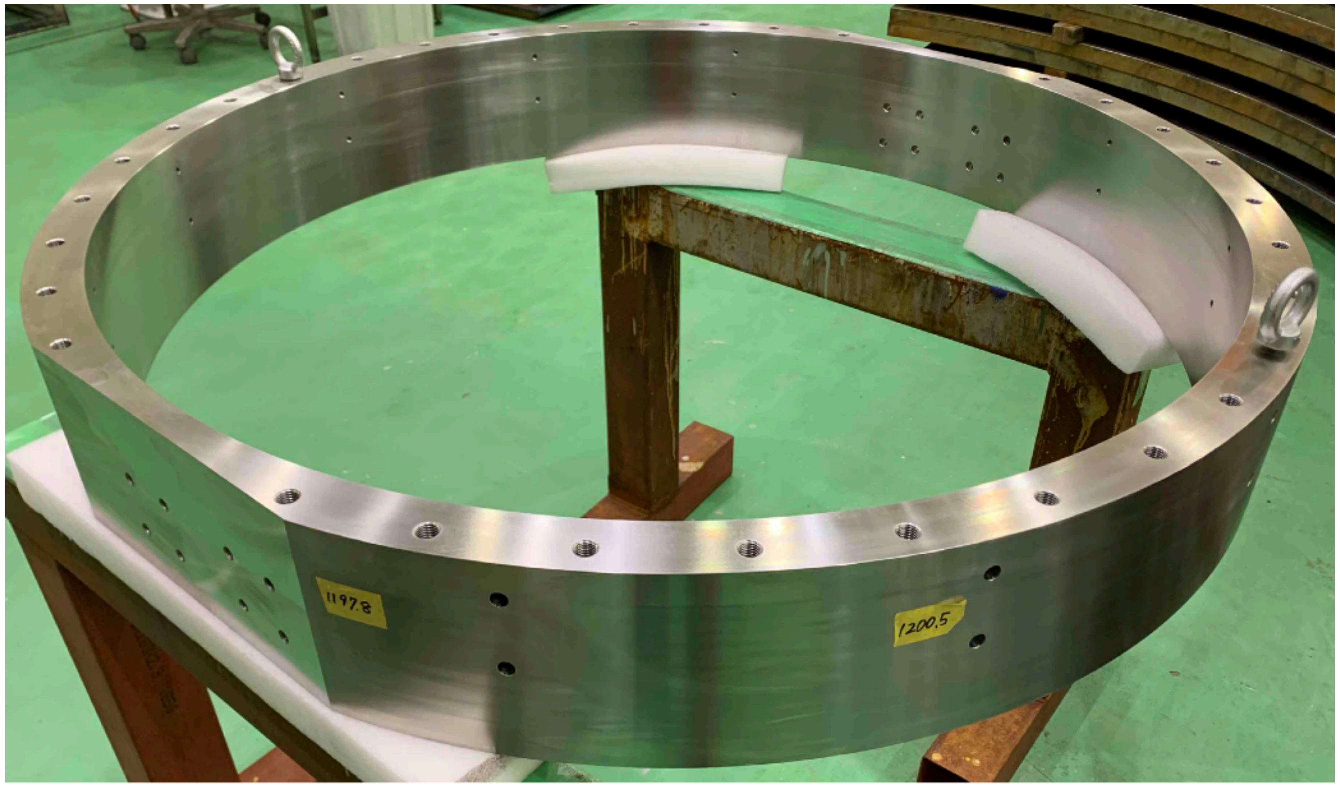
# ECAL Construction for Phase-I

- **Final detector design for Phase-I is fixed.**
  - 1024 crystals in total
    - 256 modules
    - approx 1/2 the final ECAL (Phase-II)
- Crystal support structure, pressure vessel, end-flange, are completed.

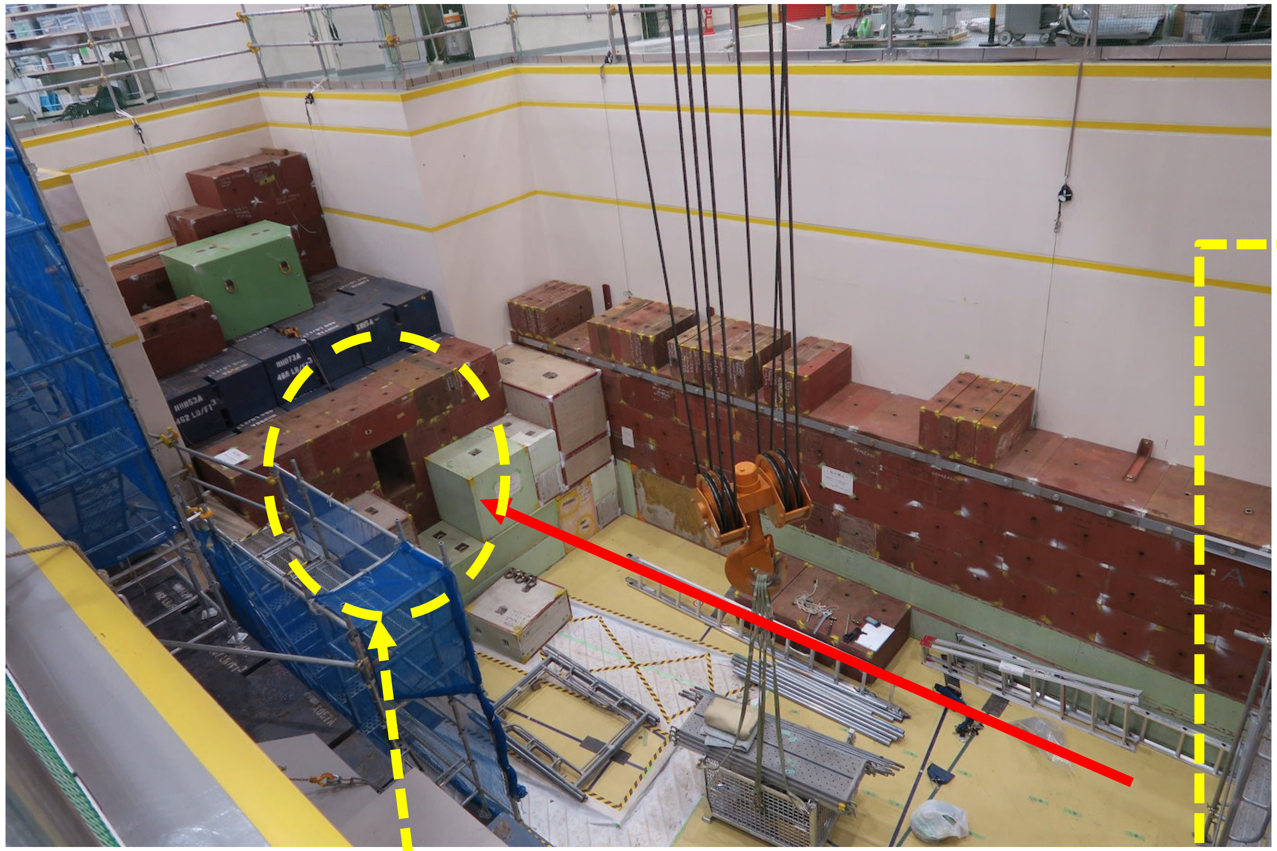
👉 **Crystal installation will start soon !!**

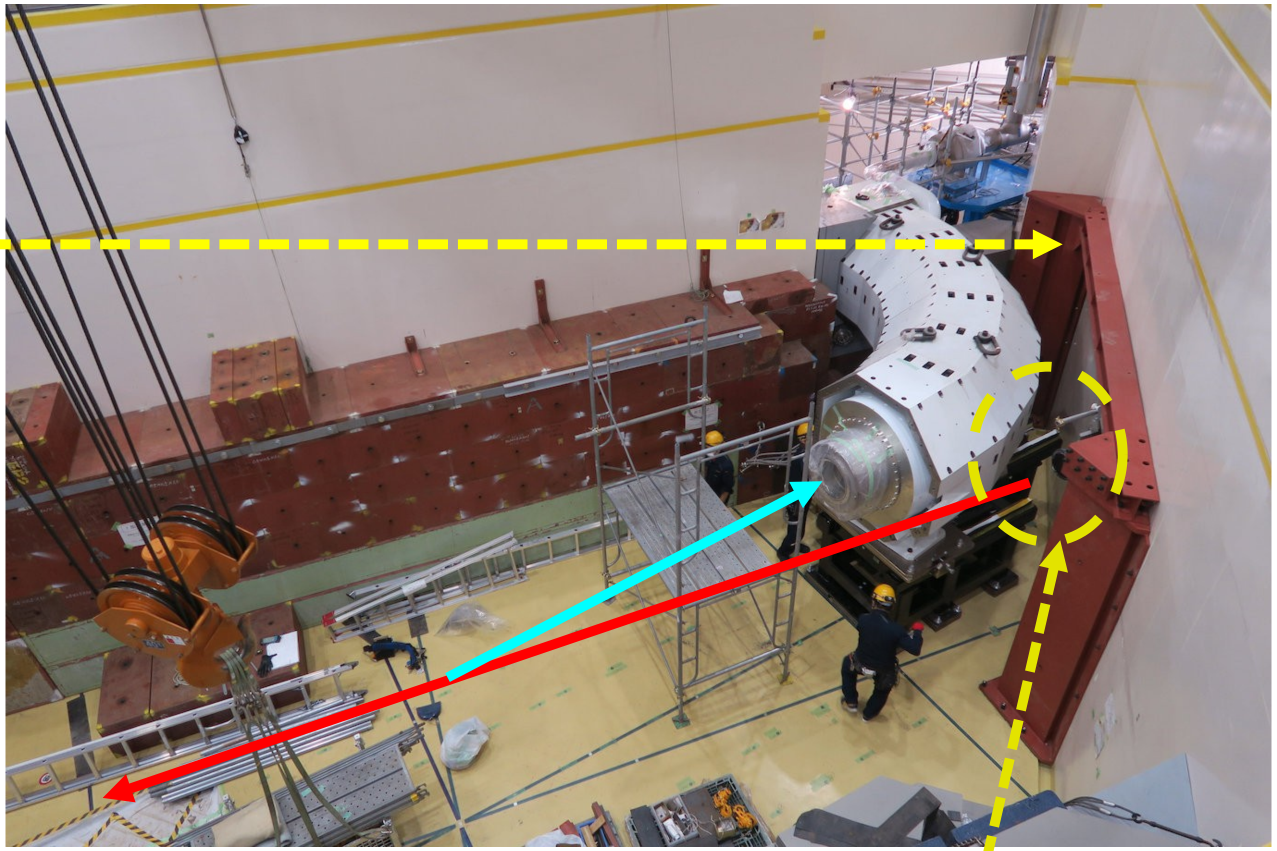




# Prospects towards COMET Phase-I



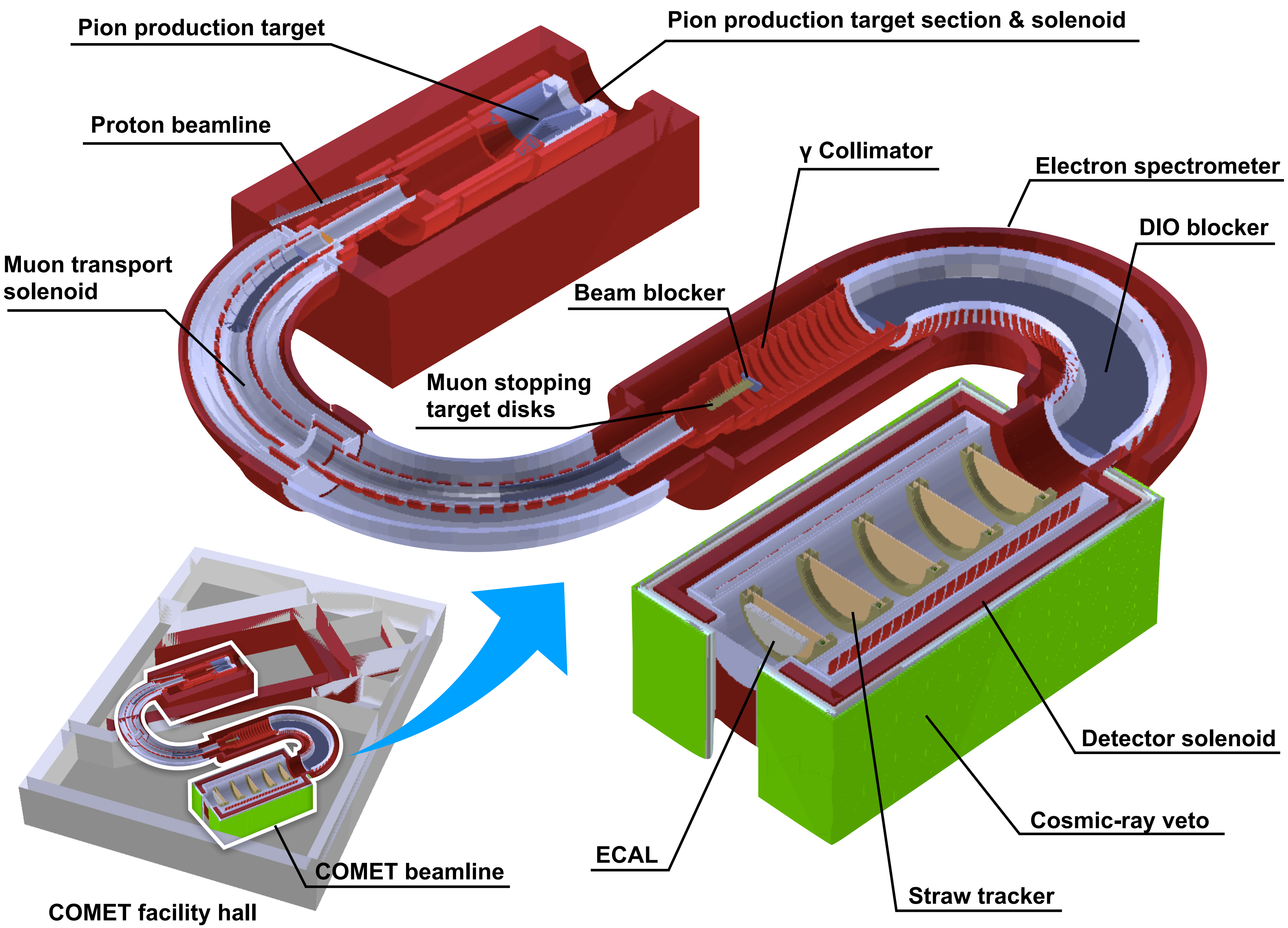


- At the J-PARC Hadron-Experimental-Facility, C-Line (primary proton beam line dedicated for COMET) is under construction, expected to be completed by the end of JFY2021.
- In JFY2022, low intensity beam commissioning (COMET Phase-$\alpha$, 200W = 1/16 of Phase-I) is planned. StrECAL might be partially tested.
- In JFY2023, StrECAL for Phase-I will be completed, and ready for beam measurement at COMET Phase-I.

# Towards COMET Phase-II

# What will be different from Phase-I ?

- Final detector for Phase-II would be basically same as Phase-I.



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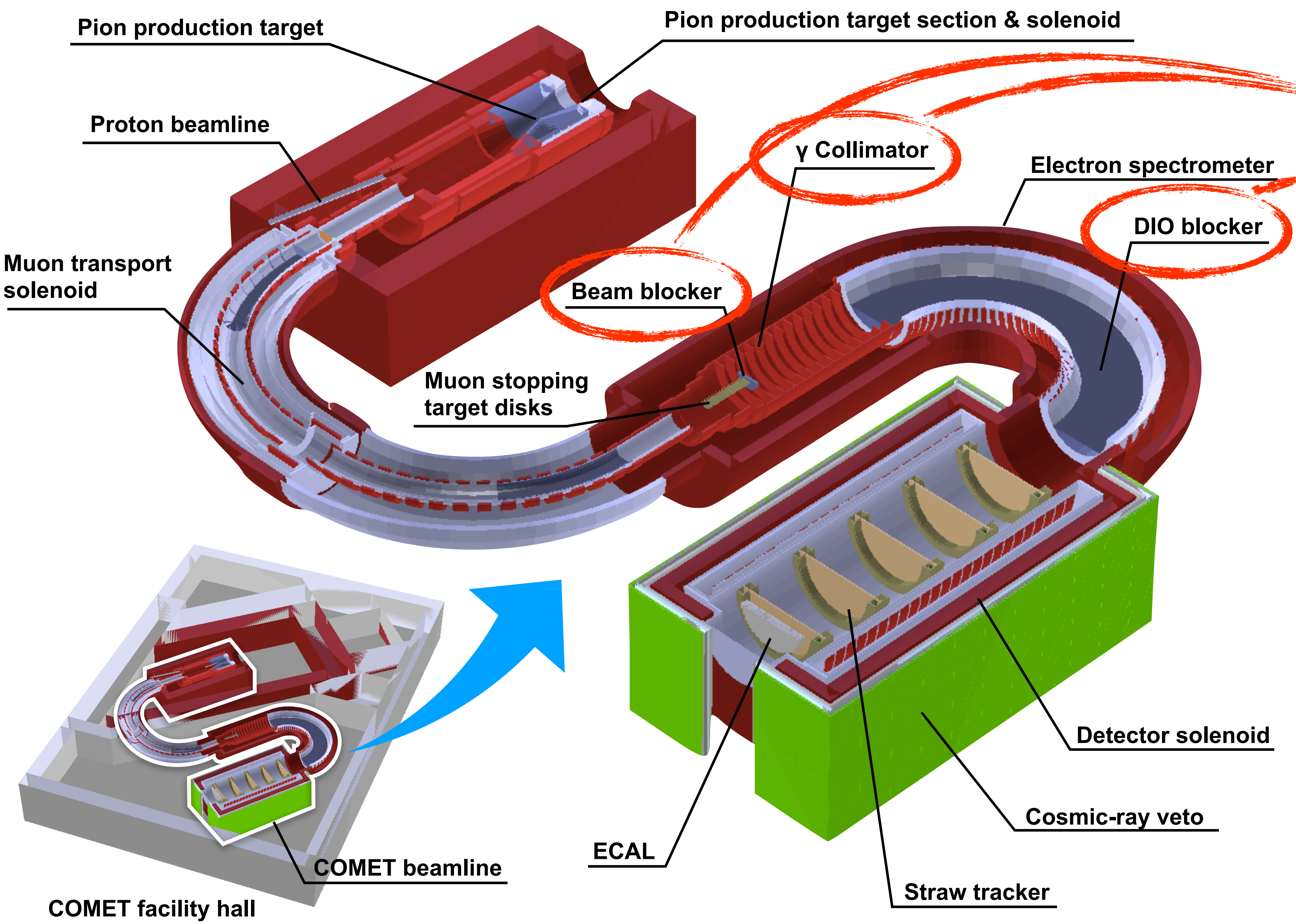


Need to be optimized by the result from Phase-I beam measurement

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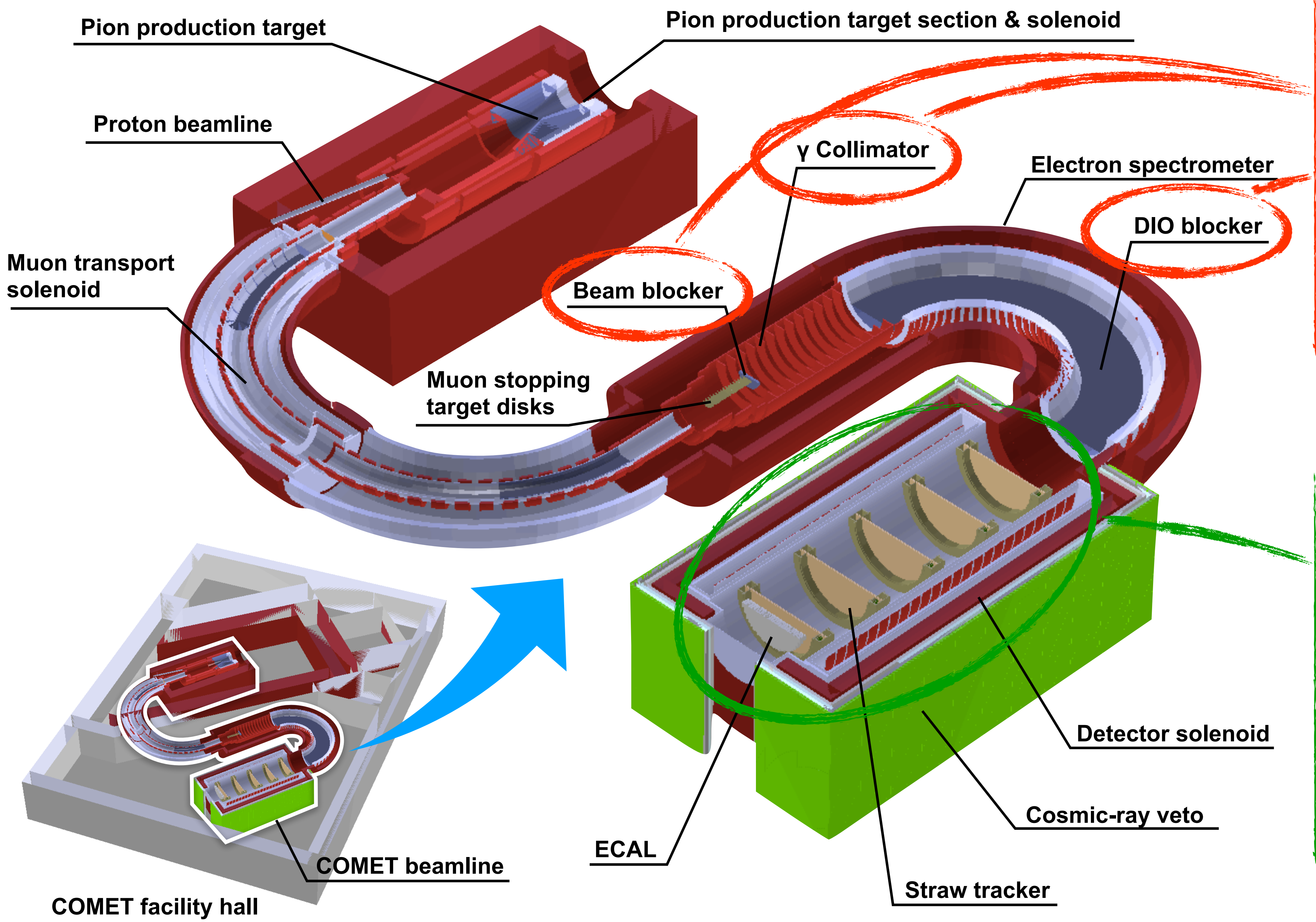


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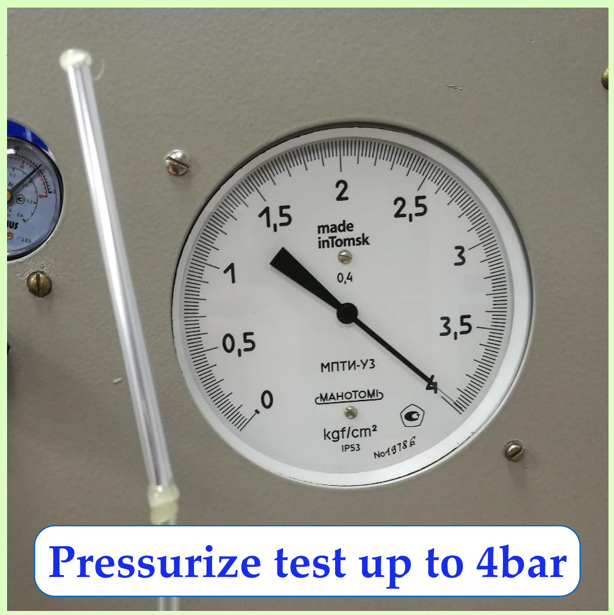
Expected to be almost same as Phase-I, but some upgrades will be made.

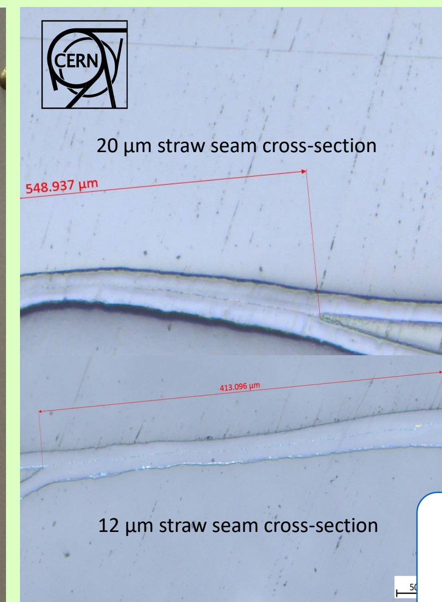
# Detector Upgrades

- **Straw will be upgraded** with a **thinner/smaller** straw tube
  - **$^{t}$12 μm/ϕ4.8mm** straw was recently developed by JINR COMET group
  - Collaborating with CERN NA62 group to utilize this as an actual tracker

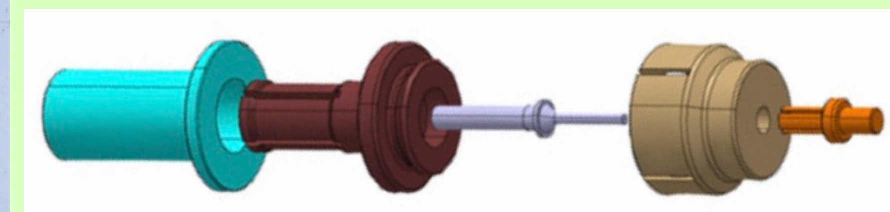
Samples of new straw



Pressurize test up to 4bar




SEM survey @ CERN, to investigate a seam of welding



Design work for end-plug and wire contact

- ECAL upgrades; Naturally, # of LYSO crystal will be increased for Phase-II as designed. (Need to be doubled at least)
  - FE-electronics might be upgraded by experiences at Phase-I.
    - In particular, radiation tolerance might be an issue.
    - Output for trigger might be optimized reflecting the Phase-I results.
  - LYSO crystal ?

# — Conclusions —

- COMET experiment aims to search for a μ-e conversion with an excellent sensitivity of $10^{-17}$ to explore the new physics beyond Standard Model.
  - To realize the experiment efficiently, dual-staged approach is employed.
- StrECAL system (= “straw” tracker + “Electromagnetic CALorimeter”) was originally designed for the “full” COMET (=Phase-II)
- In Phase-I, two experiments will be conducted; “beam measurement” and “μ-e conversion search”
  - Beam measurement will be carried out by StrECAL
  - StrECAL for Phase-I is real prototype for Phase-II StrECAL
- StrECAL construction
  - Design for Straw tracker and ECAL is finally fixed by R&D with test-beam.
  - Straw assembly → Station #1 completed. Station #2 starts soon.
  - ECAL assembly → Support structure completed. Crystal installation starts soon.
  - Aim to be ready in 2023 for Phase-I beam measurement.
- Towards Phase-II
  - In parallel to Phase-I construction, upgrade R&D is ongoing.