Status of the COMET experiment

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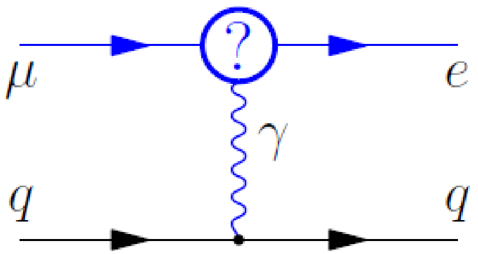
On behalf of the COMET collaboration

The COherent Muon to Electron Transition: (COMET) Experiment – the world wide collaboration

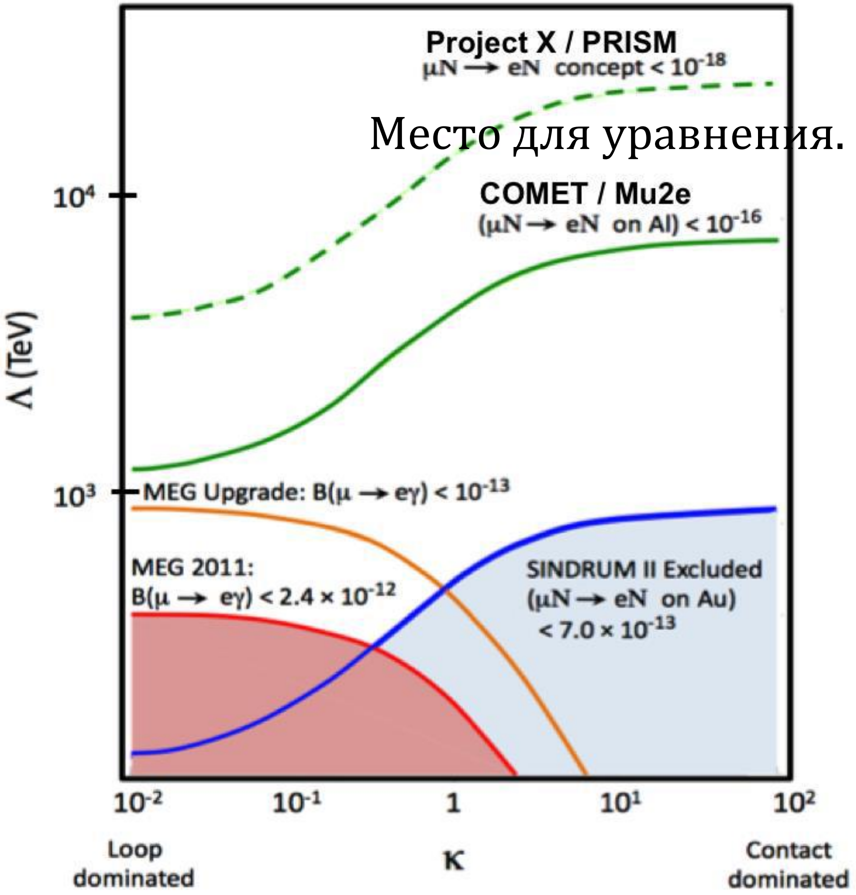
The O(200) participants from 41 institutes of 18 countries.

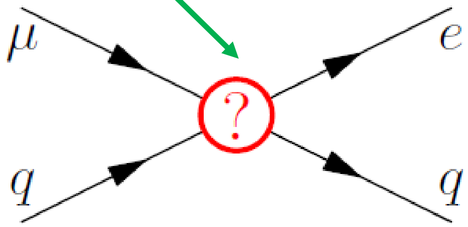
Physics motivation for search of the cLFV with muons

- cLFV is strongly forbidden in SM (Br<<10^{-54}) so the any signal is clear indication of new physics.
- BSM $\mathcal{L} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu$ & $\frac{k}{(1+k)\Lambda^2}\bar{e}\mu(\bar{q}q+\bar{e}e)$



Loop process
k<<1





Contact process
k>>1

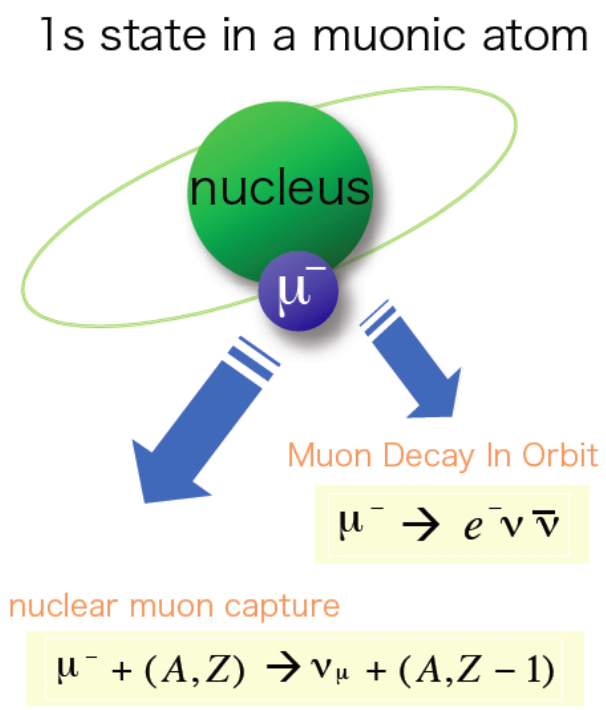
The search of the cLFV with muons

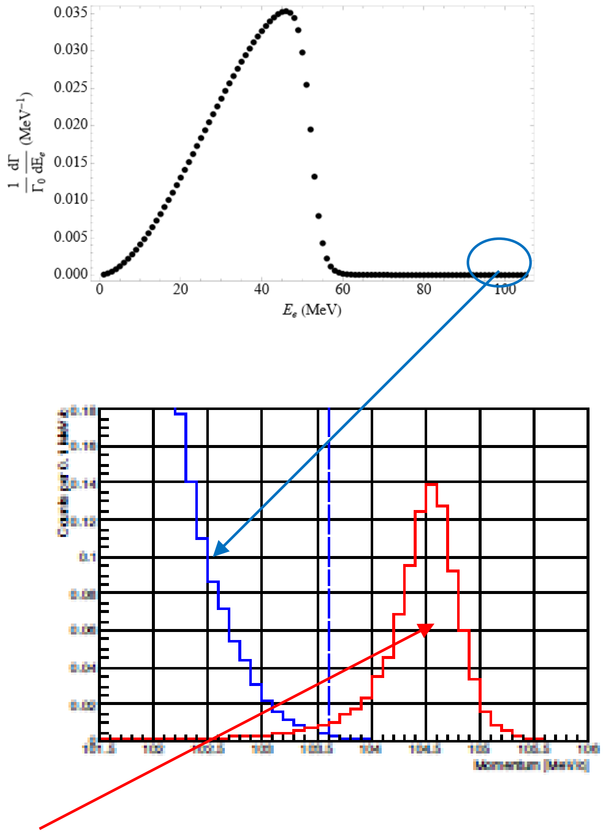
Physical Process	Sensitivity k<<1	Sensitivity K>>1	Most sensitive experiment	status
$\mu^+ \rightarrow e^+ \gamma$	High	0	MEG II	running
$\mu^+ \rightarrow e^+ e^- e^+$	Sizable	High	Mu3e	In preparation
$\mu^- N \rightarrow e^- N$	Sizable	High	COMET, Mu2e	In preparation

The sensitivity to a new physics is different in the processes
Since a new physics is unknown, it is important to study all 3 with comparable sensitivity
The muon to electron conversion has no coincidence and accidental background
specific requirements: pulsed high intensive proton beam
ultimate momentum resolution in the detection

Muon to electron conversion experiments

- The idea – use the pulsed beam and look for the delayed electron from muon capture on nucleus
- Signal electron is monoenergetic $E_e=(m_\mu-m_e-E_{binding})=104.97$ MeV (Al target)
- The physics background: decay on orbit (DIO 39%)- an extremely high momentum resolution required



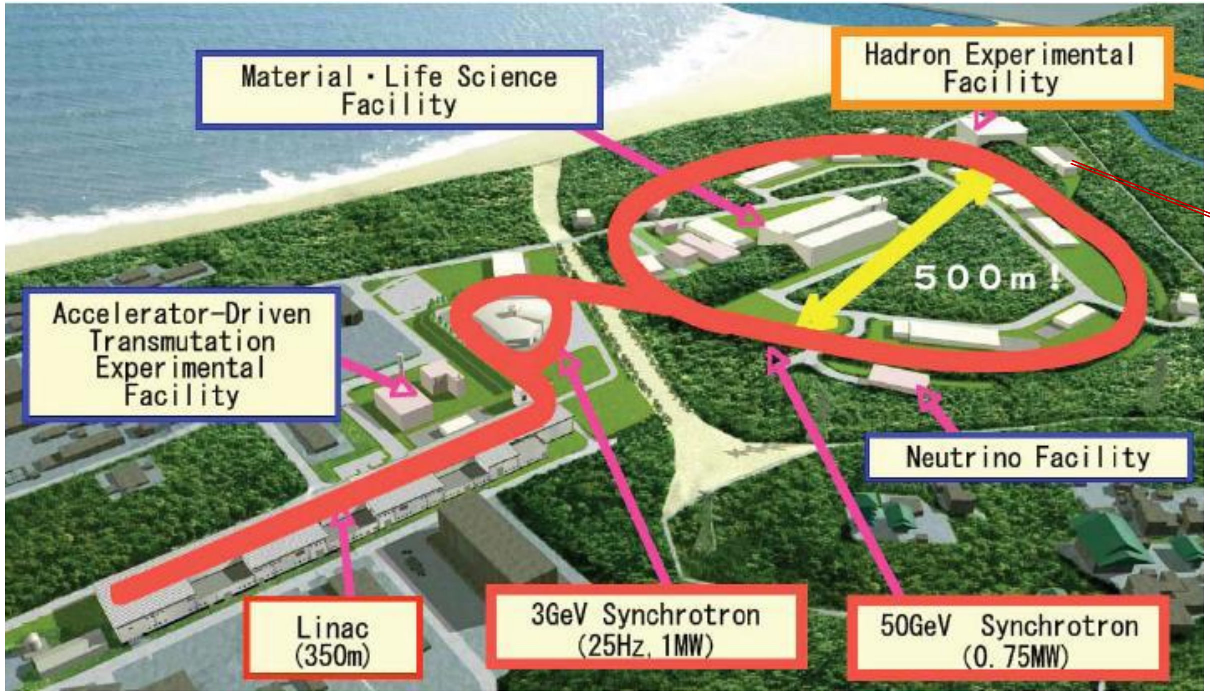


$E_e=(m_\mu-m_e-E_{binding})-E_{loss\_in\_target}$

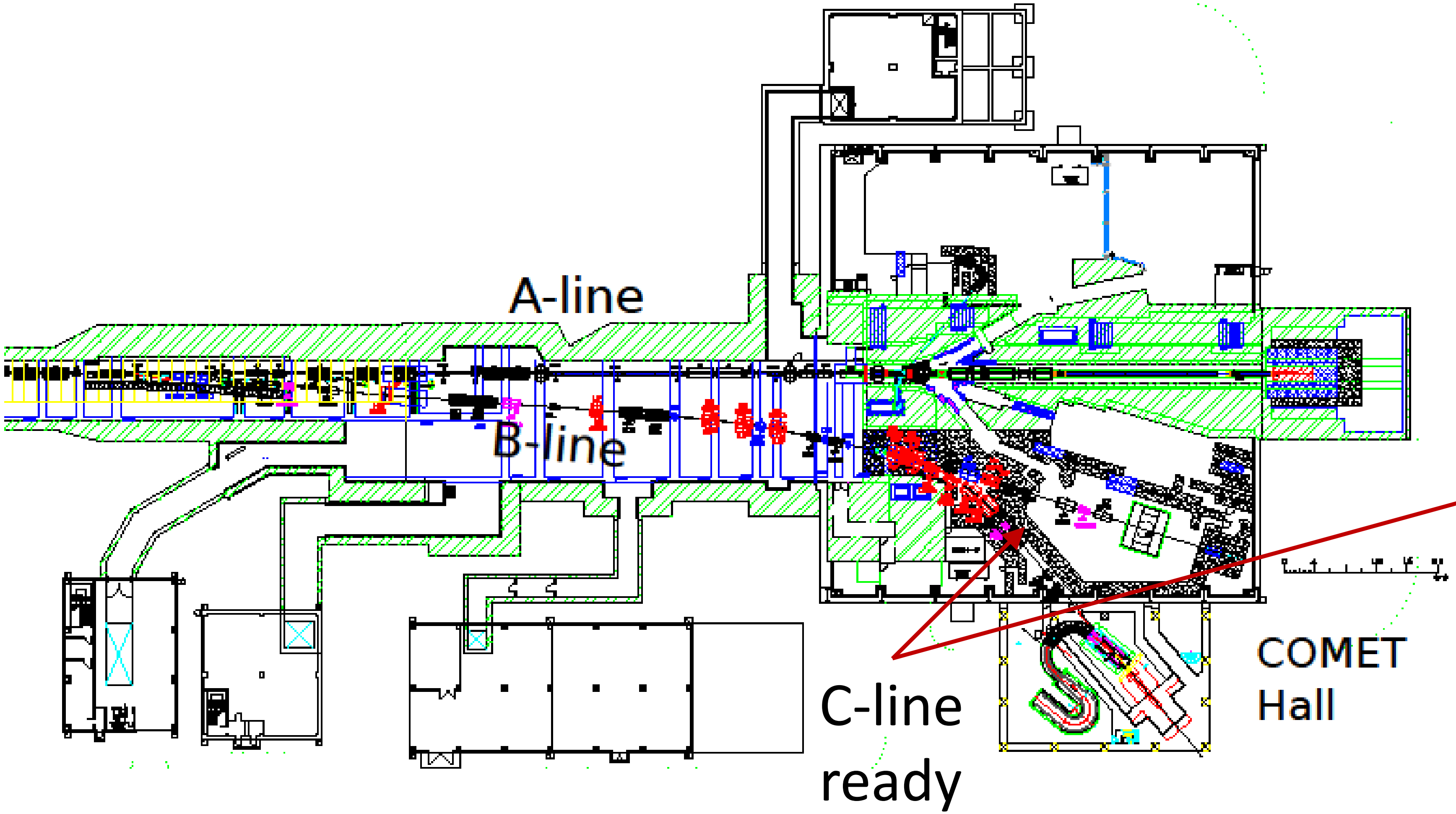
(MC *COMET Phase-I for Br=3x10^{-15}*)

The COMET experiment home

- The source of the muons: the high power pulsed proton beam with 8 GeV energy from J-PARC main ring at slow extraction.

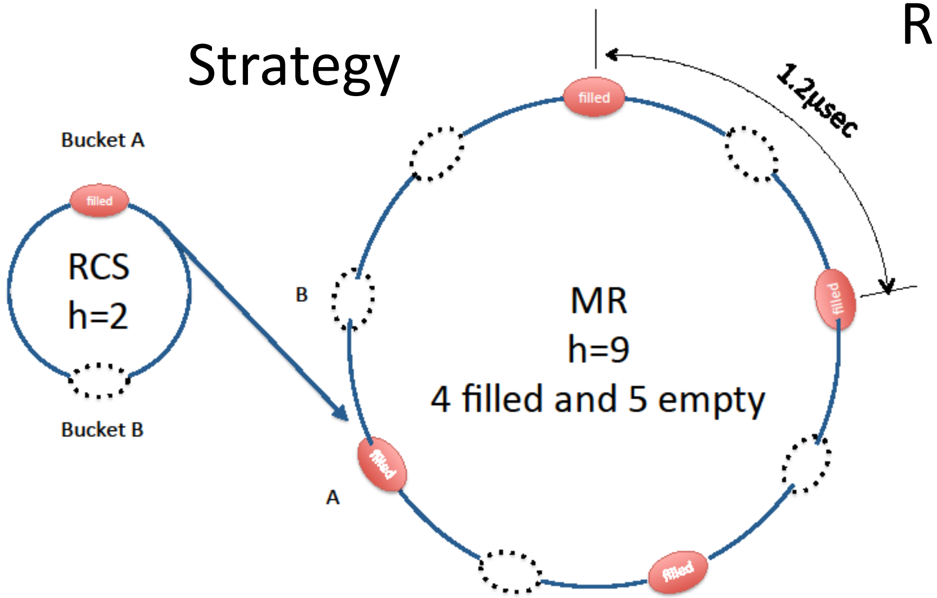


The dedicated proton beam line

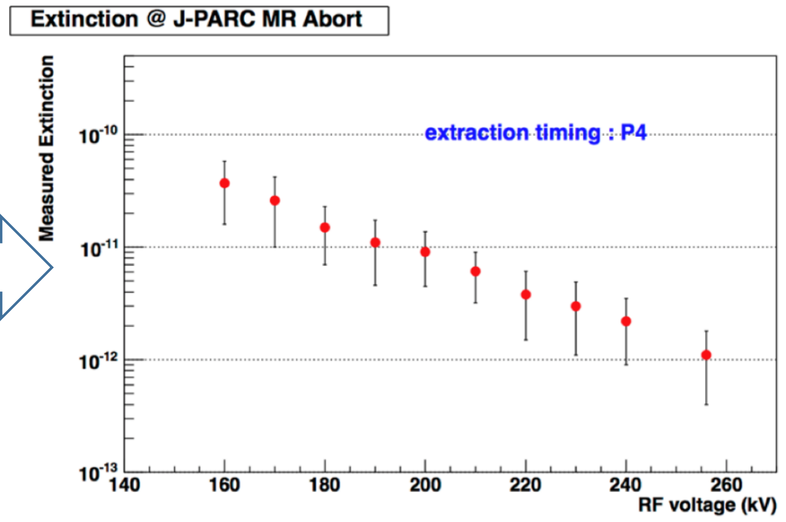


The proton extinction

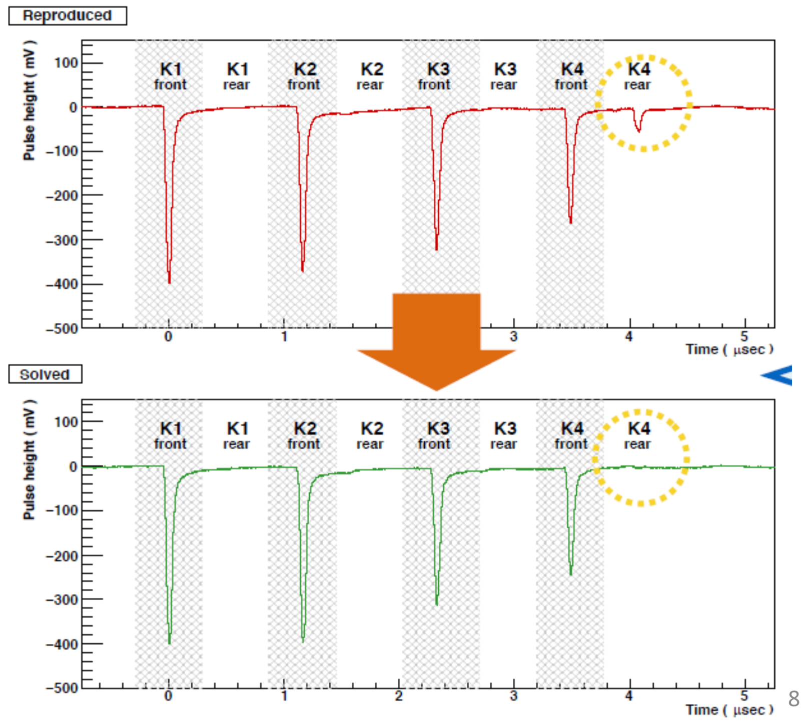
Strategy



RF tuning



Extraction kicker
Tuning



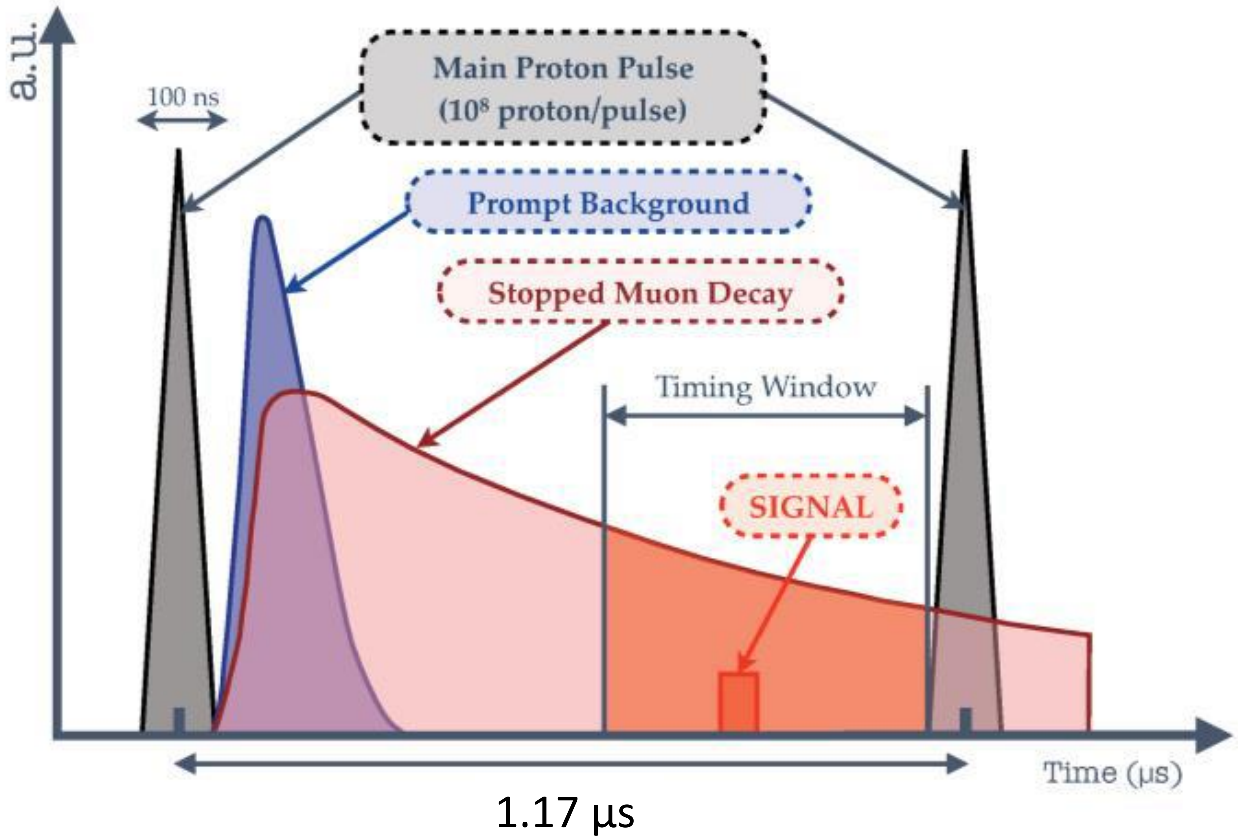
The goal: proton extinction $R(N_{leak}/N_{pulse})<10^{-10}$

Measurement at main ring (2018) $<10^{-10}$

Measurement at hadron hall (2021) $<3.2\times10^{-12}$

(confirmed at 2023)

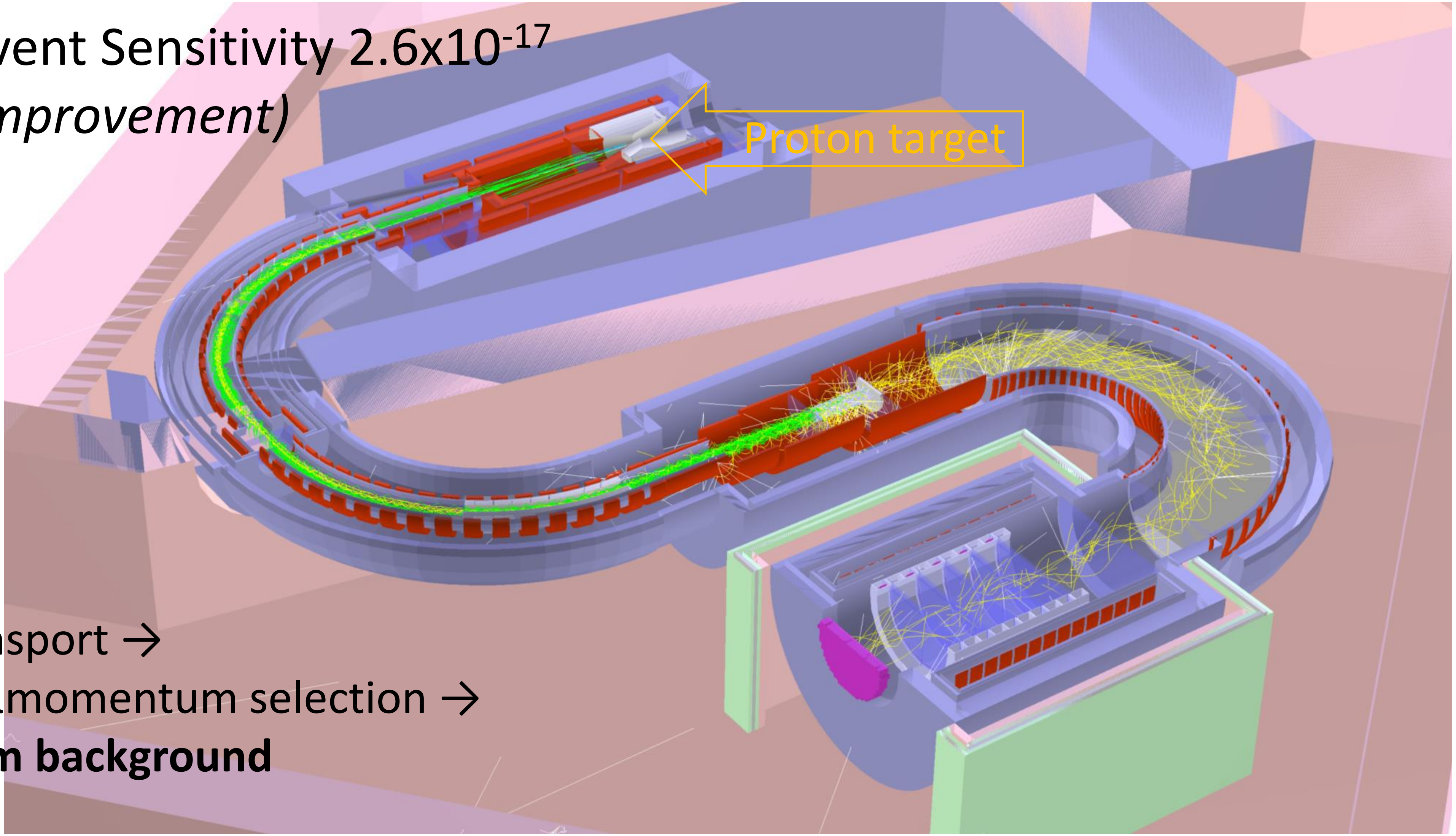
Time diagram



The time diagram determinates material of muon stopping target: Al ($\tau_{\mu\text{-atom}}$=864 ns)

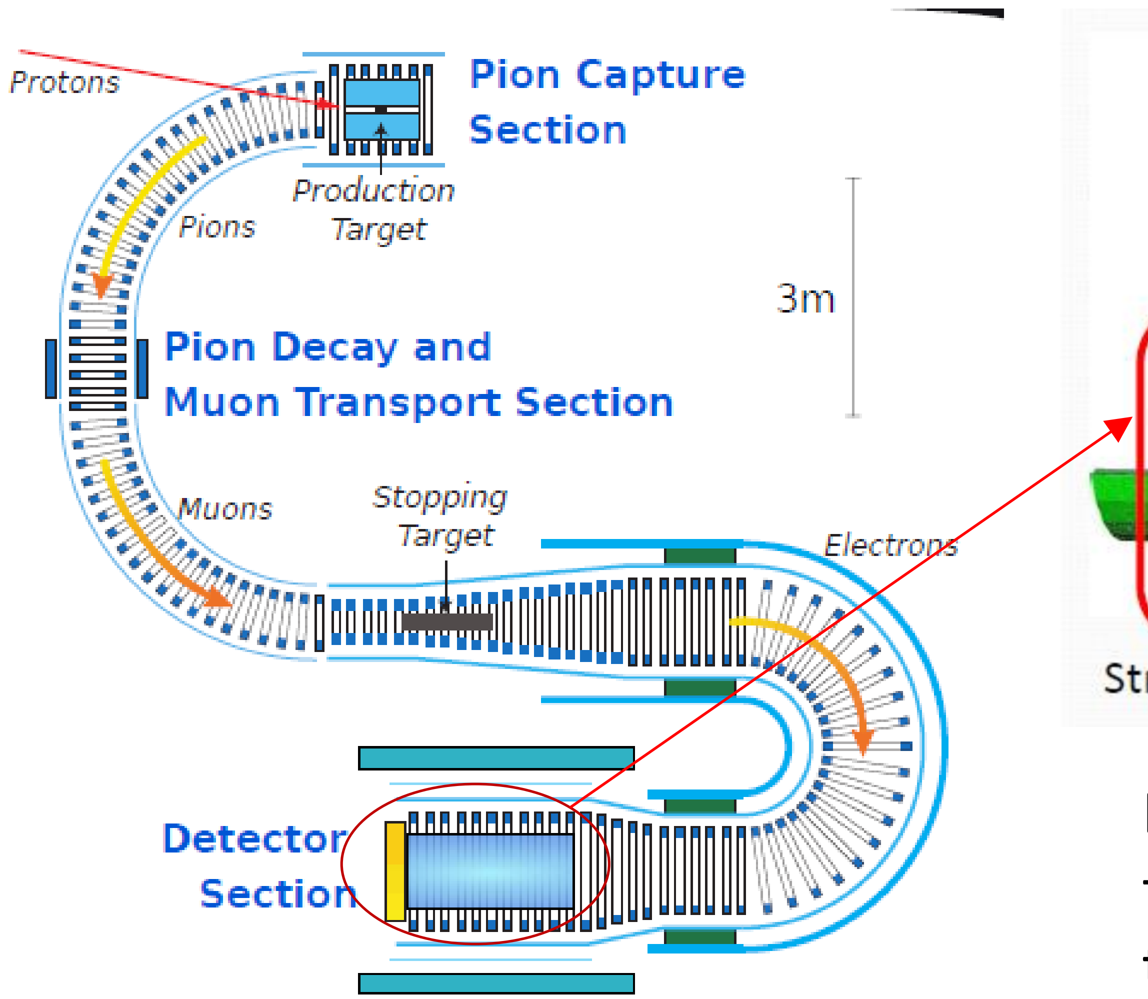
The COMET experiment

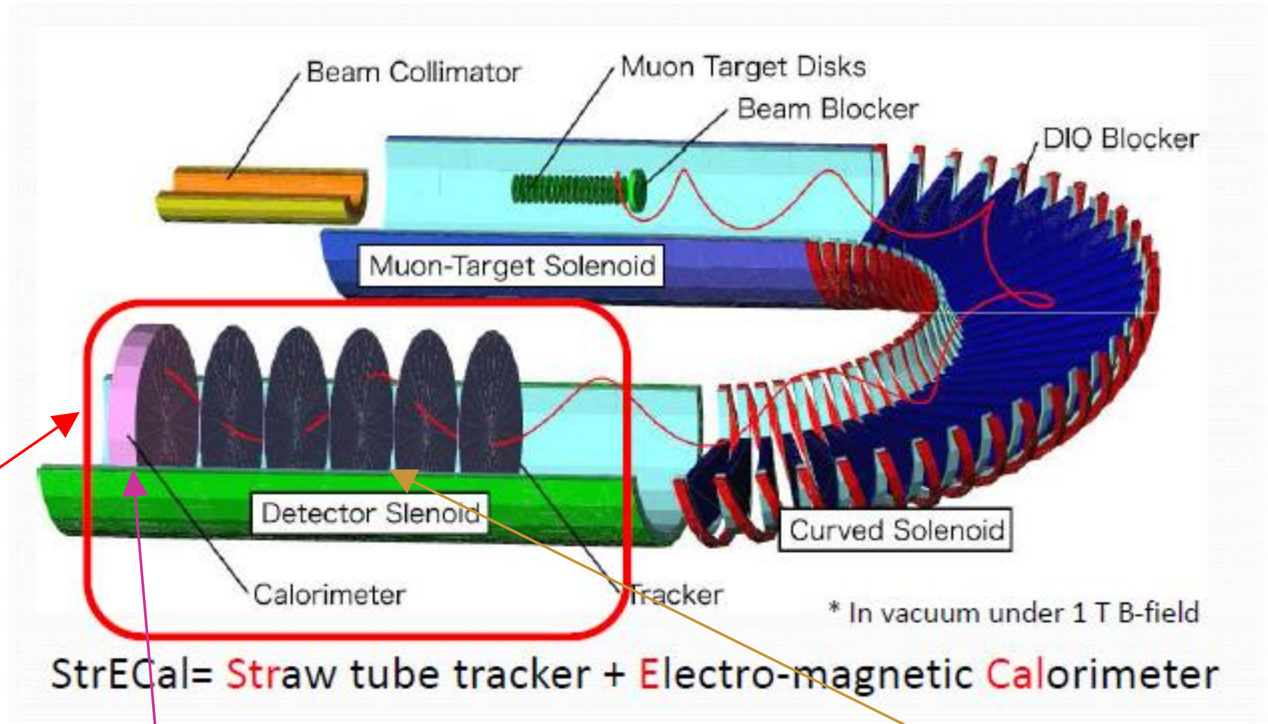
GOAL: Single Event Sensitivity 2.6×10^{-17}
(10000 times improvement)



Longer muon transport →
better charge&momentum selection →
smaller beam background

The COMET experiment



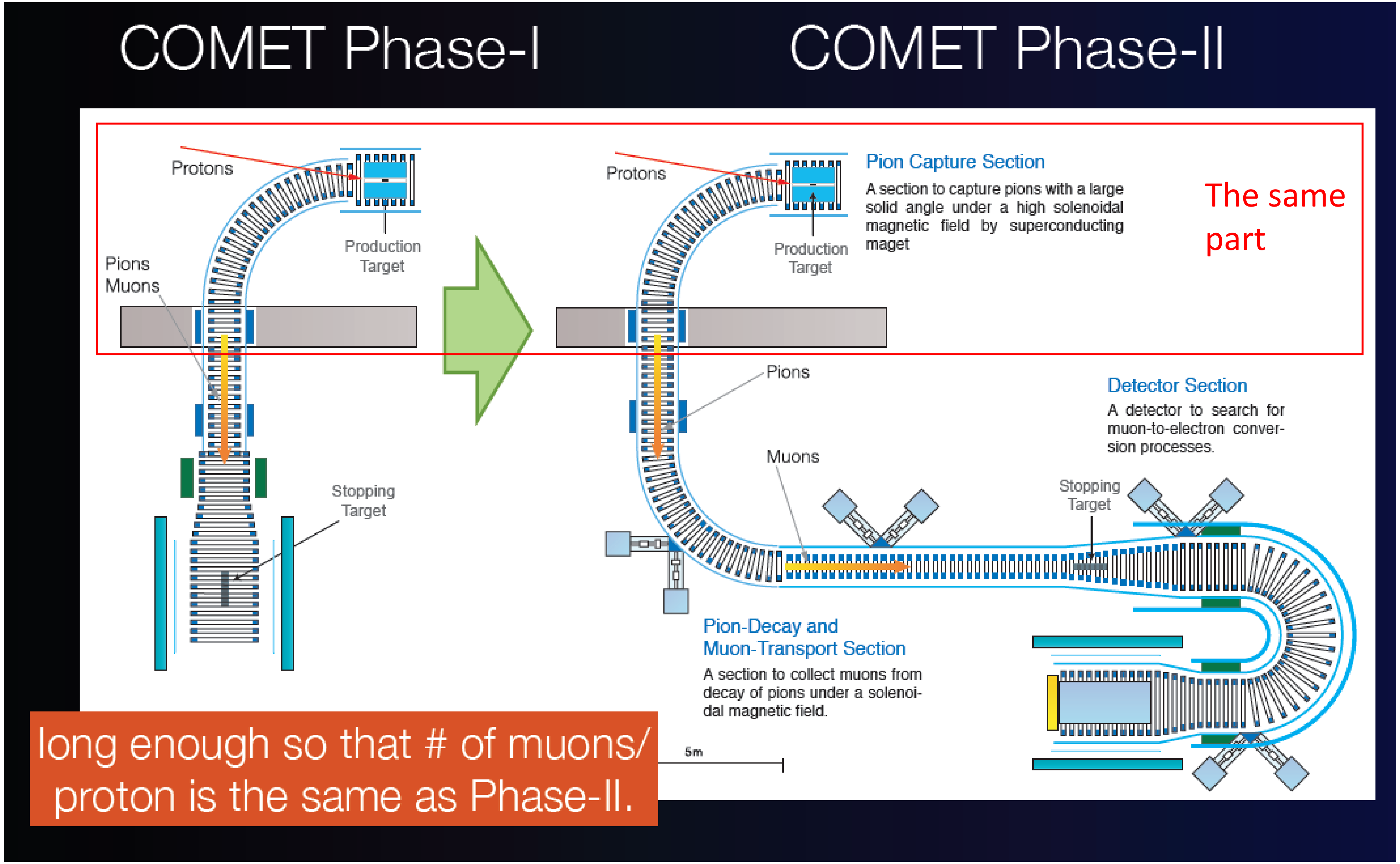


Ecal ~ 2000 LYSO crystals for energy measurements, trigger and PID

5x4 planes of light straw tubes for tracking

Testing of prototypes confirms main parameters: $\sigma_E/E<5\%$ $\sigma_p<150$ keV/c

Two phases approach

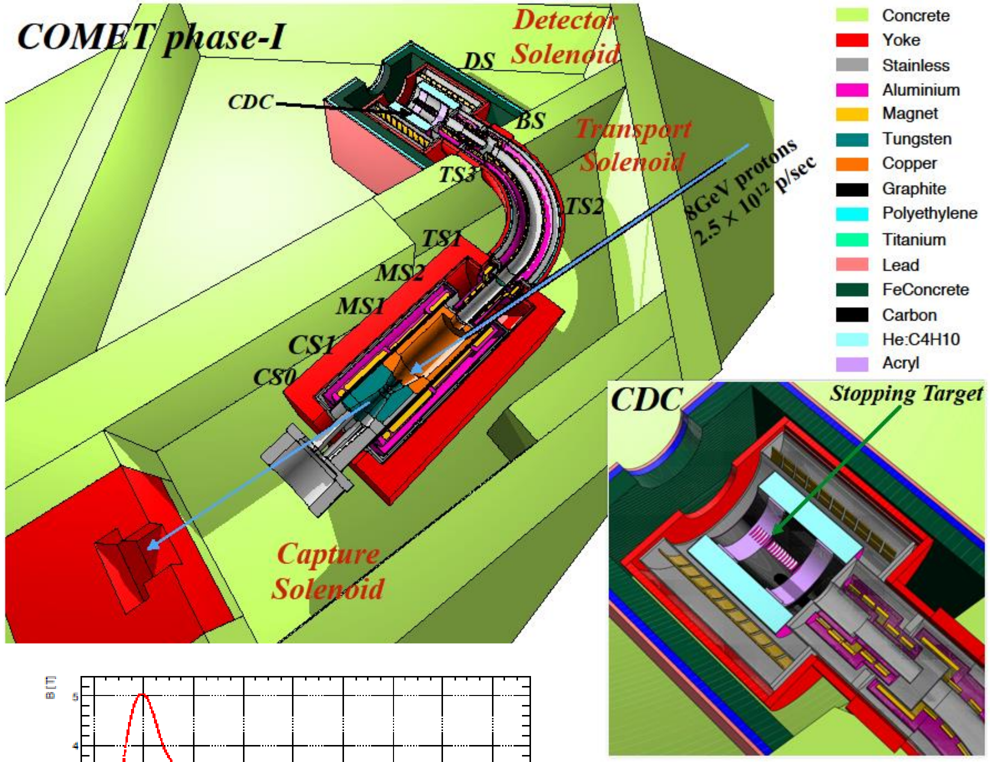


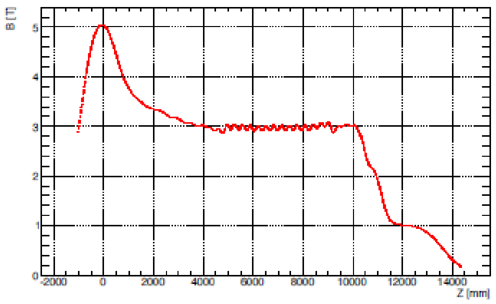
The two phases approach

Parameter	Phase-I	Phase-II
Bending	90 degrees	360 degrees
SES	$3x10^{-15}$	$3x10^{-17}$
Beam power	3.2 kWt	56 kWt
POT	$3x10^{19}$	$3x10^{21}$
Stopped muons on target	$1,5x10^{16}$	$1,5x10^{18}$
Running time	O(100 days)	O(1 year)

The Phase-I will be discussed below

The target, pions and muons production and transport





- Key points:
- Target – graphite 70 cm long
- Pion capture solenoid – 5 T Dia=1324 mm
- Transport solenoid – 3 T Dia=O(500 mm)
- Detector solenoid – 1 T Dia=2156 mm
- Solenoid matching – adiabatic with implementation of the special bridge solenoid

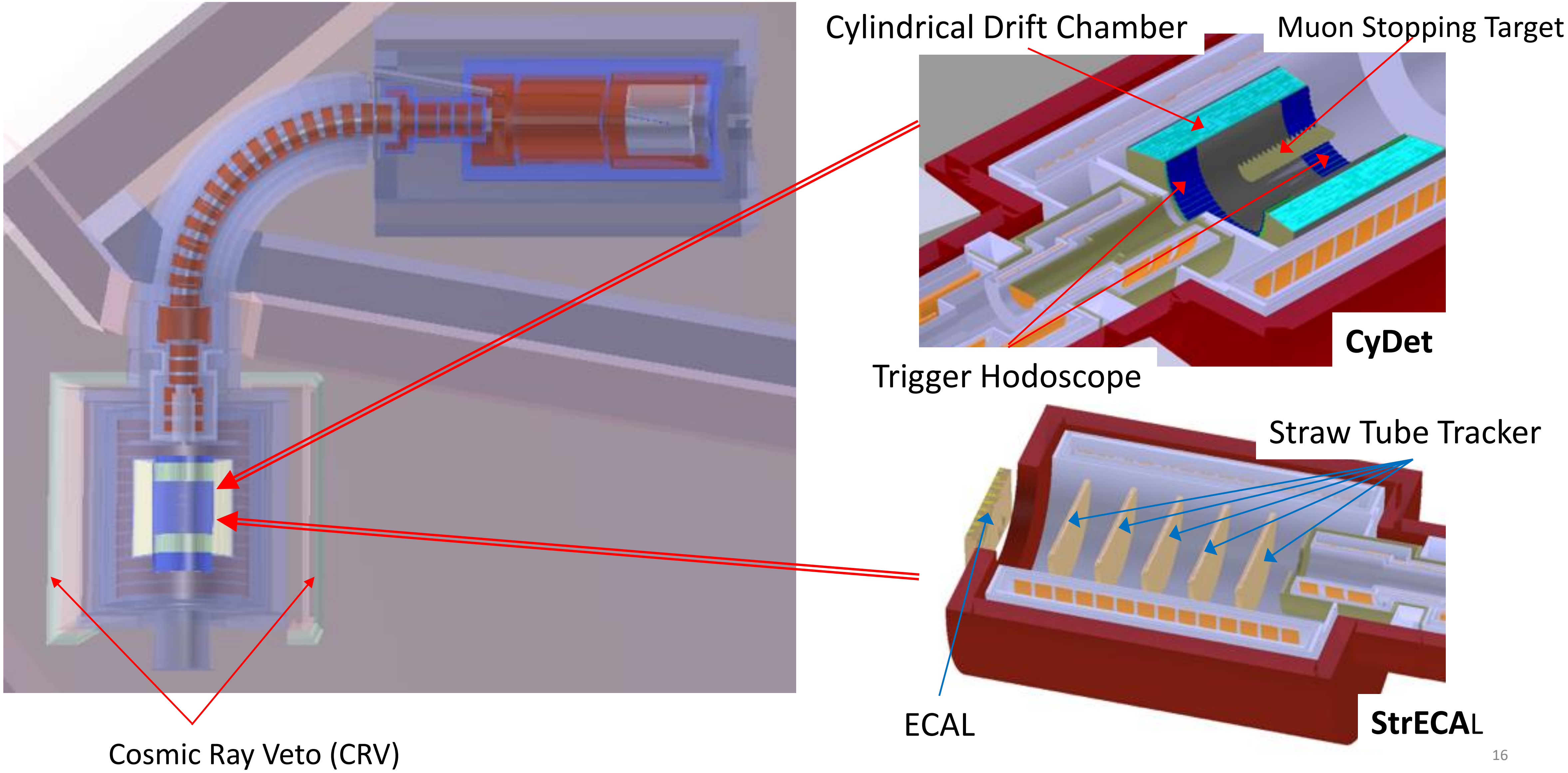
2 detectors for Phase-I

- **Cylindrical detector (CyDet)**
- Base on custom cylindrical drift chamber and sophisticated trigger counters hodoscopes
- The goal:
  to perform physics measurements

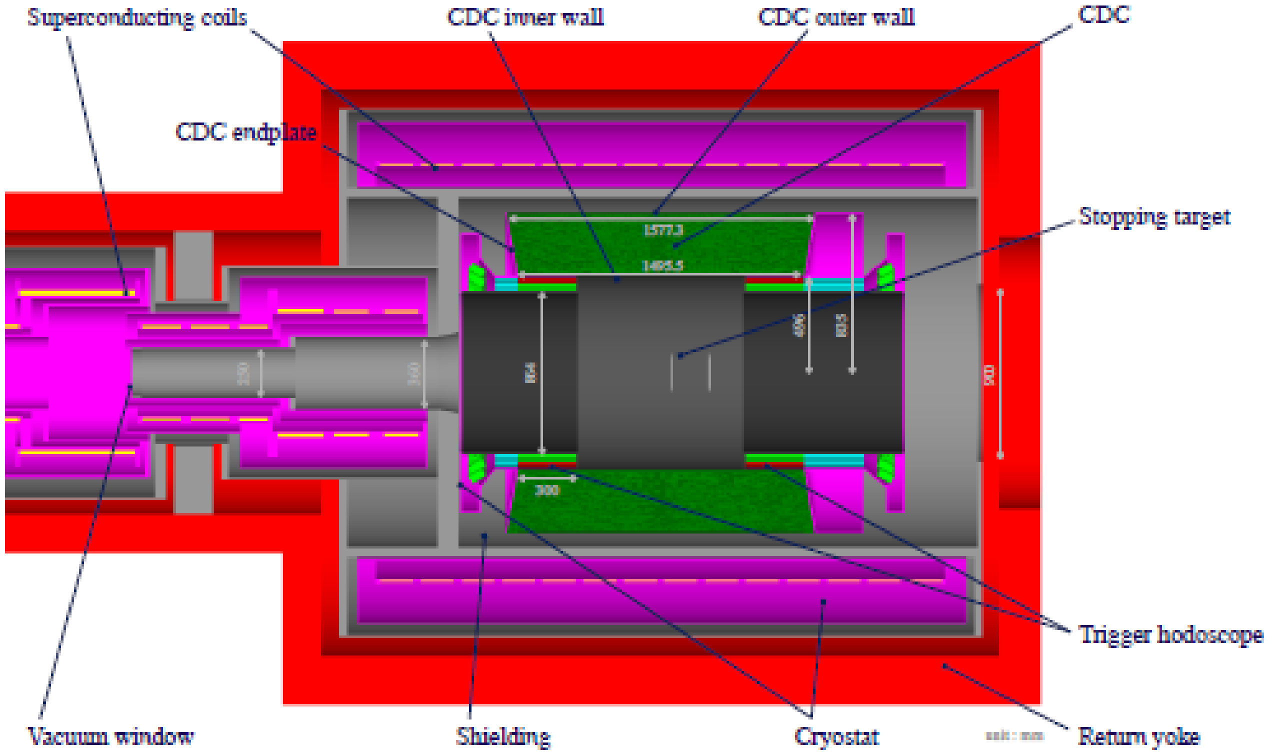
- **Planar detector (StrEcal)**
- Base on straw tubes and electromagnetic calorimeter as planned for the Phase-II.
- The goal:
  large prototype test for Phase-II beam background measurements

The both detectors will uses the same solenoid and operates in turn

2 detectors for Phase-I



Cydet: layout

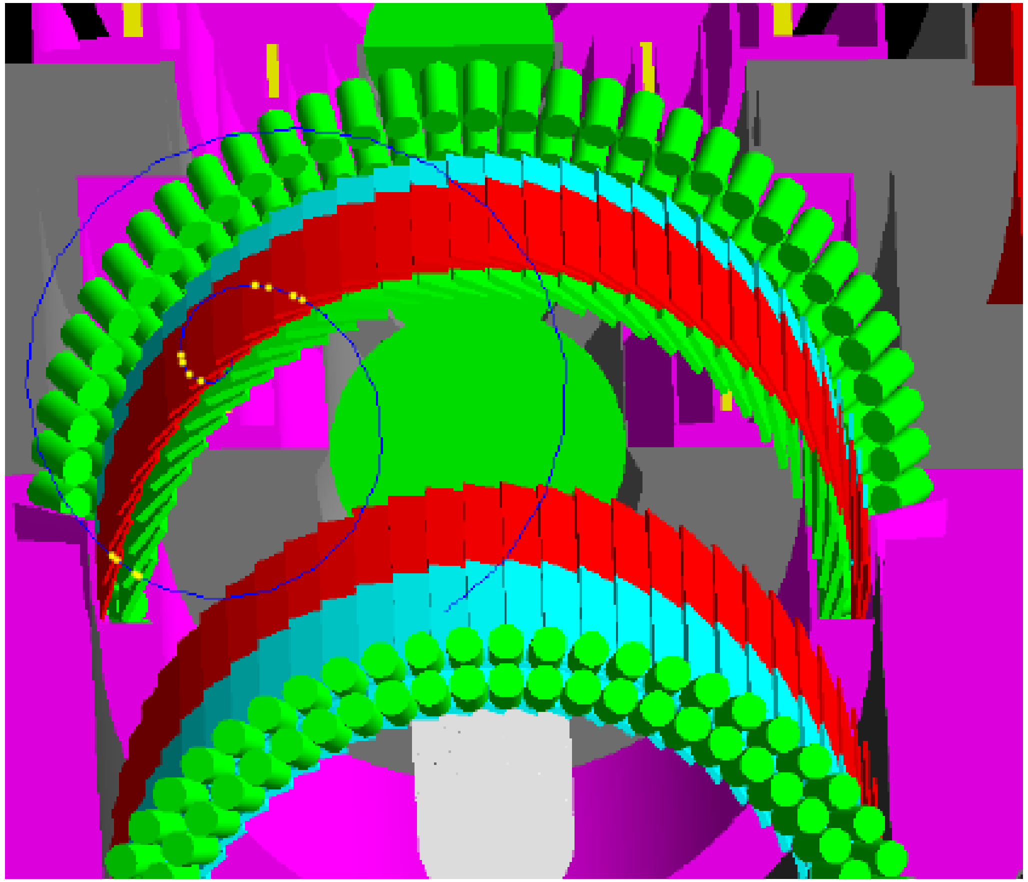


Muon stopping target: 17 aluminum disks of 0,2 mm thickness and 100 mm radius with 50 mm spacing

The main drift chamber parameters

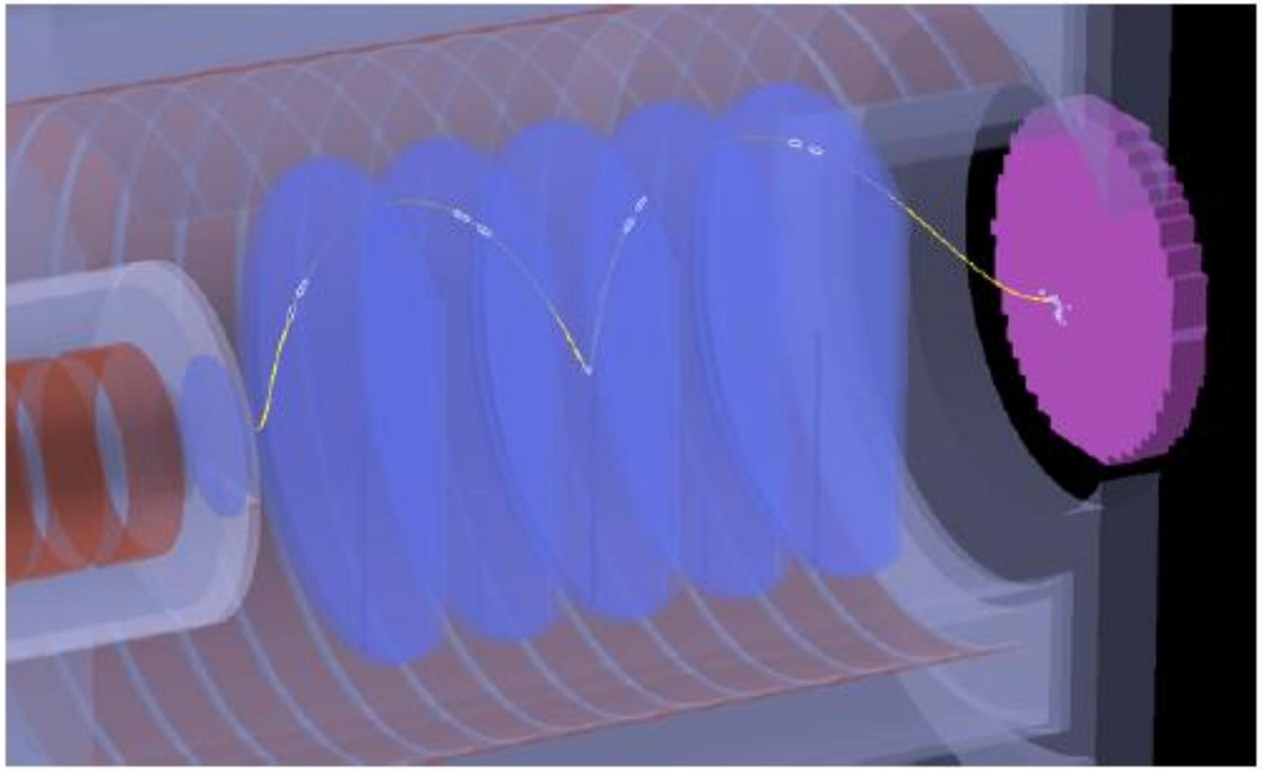
- Material of walls – carbon fiber reinforced plastic (CFRP)
- Inner wall radius, length and thickness – 496, 1495 and 0,5 mm
- Outer wall radius, length and thickness – 840, 1577 and 5 mm
- Sell structure – almost square containing 20 alternative stereo layers with angles of 64-75 mrad (innermost and outermost are guards ones)
- Sense wires – 4986 Au plated W with diameter 25 μm (50 g tension)
- Field wires – 14562 Al with diameter 126 μm (80 g tension)
- Gas mixture – He:i-C_4H_{10} (90:10%)
- Momentum resolution – better 200 keV/c at 105 MeV/c

Trigger hodoscopes



- Red – Ultra fast scintillator EJ-230 300x90x5 mm
- Blue – Cherenkov counter base on UV-transparent acrylic plastic 300x90x10 mm
- Both scintillator and Cherenkov hodoscopes consists of 2 layers, with shifted on half of width counters *(start data taking without Cherenkov hodoscopes)*
- Readout by SiPM

StrEcal detector



The proposed layout of the detector for Phase-II
The blue – planes of the straw tubes
The pink – wall of the ecal crystals

StrEcal detector

- Straw tubes:

  Diameter – 9.75 mm

  Outer wall – 20 microns thick Al-coated mylar (a thinner wall is under study)

  Anode wire – gold plated tungsten 25 microns diameter

  Length – from 692 to 1300 mm

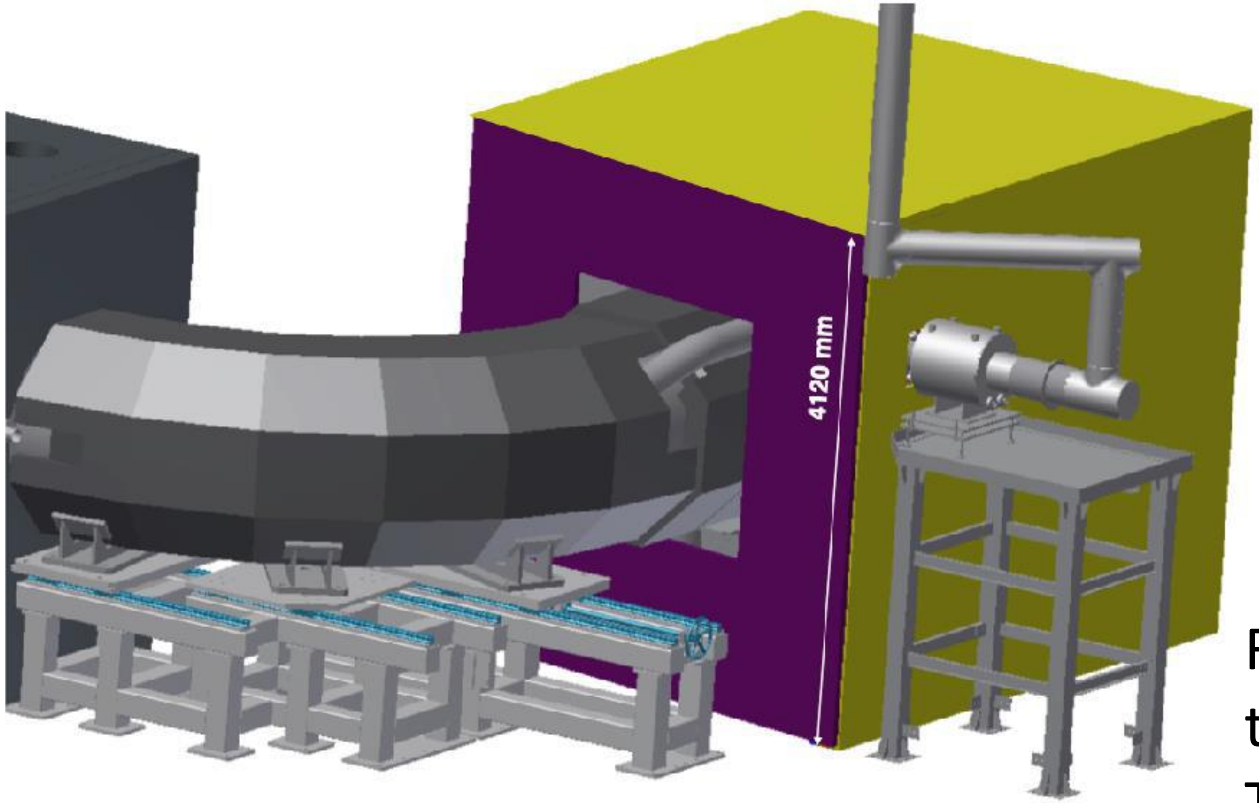
  Gas mixture – Ar-Ethane 50:50

StrEcal detector

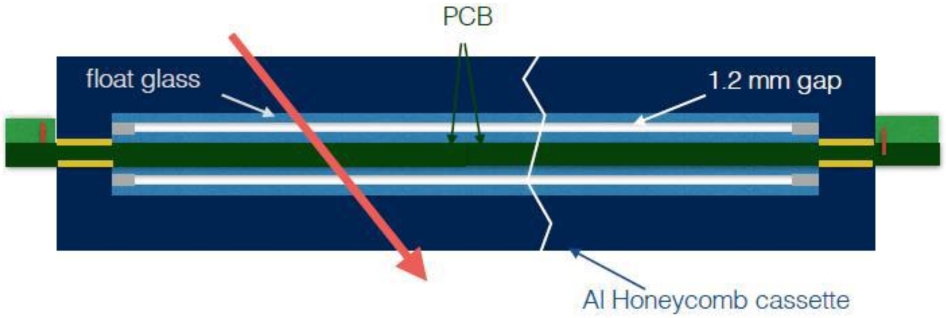
- Electromagnetic calorimeter
  - Scintillator – 20x20x120 mm LYSO crystals
  - Light readout – Hamamatsu APD S8864-1010 with 10x10 mm sensitive area
  - Electronics – custom design low noise fast amplifiers
  - Location – crystals and APD are inside vacuum volume to minimize multiple scattering and noise while electronics is outside vacuum for easier cooling
  - Measured energy resolution – better than 5% for the 105 MeV electrons
  - ~500 crystals will be used for Phase-I (out of a total 1920 needed for Phase-II).

Cosmic Ray Veto (CRV)

Yellow: plastic scintillators (4 layers)
Purple: RPC detector



The RPC design in progress



Full size prototype module is made and tested with radioactive source
The measured cosmic ray suppression 99.86% is close to the design value

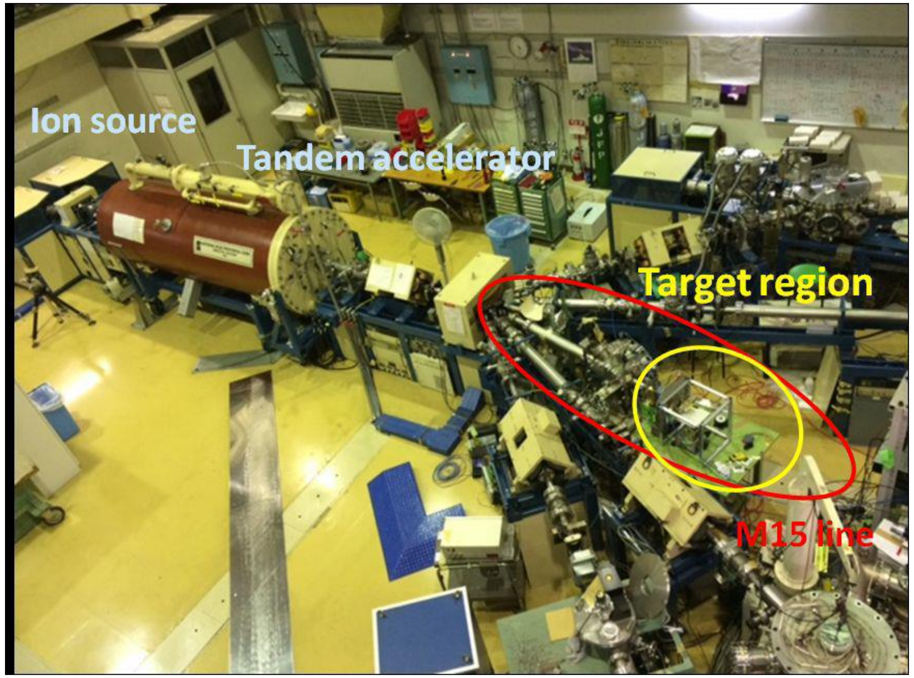
The important issue: radiation hardness

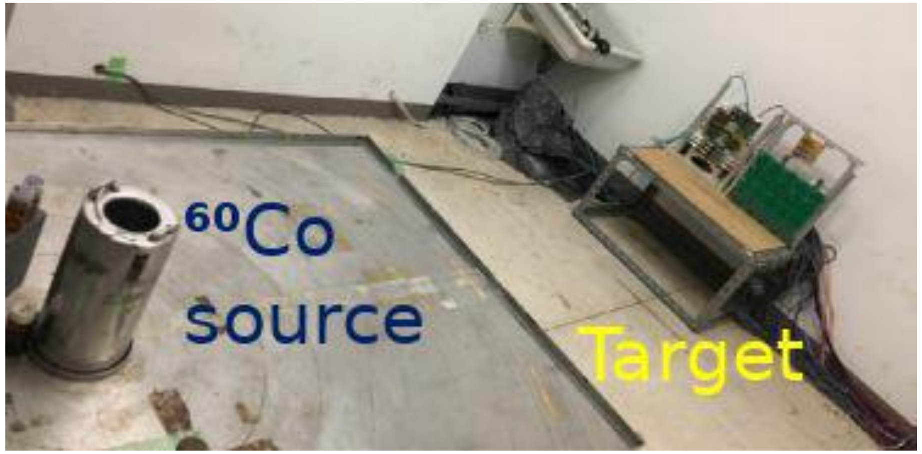
Expected irradiation during Phase-I
Neutrons – up to $10^{12}/cm^{-2}$ (1 MeV equivalent)
Gammas – up to 1 kGy

All parts were tested many times
As a result, the proper ones are selected

The neutron irradiations were done by using of
3 MeV deuteron beam on Be target
at tandem accelerator (Kobe university)

The gamma irradiations were done with 60Co source
At Radioisotope Research Center,
(Tokyo Institute of Technology)





The Phase-I performance (based on detail MC study)

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	0.93
Timing window	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
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

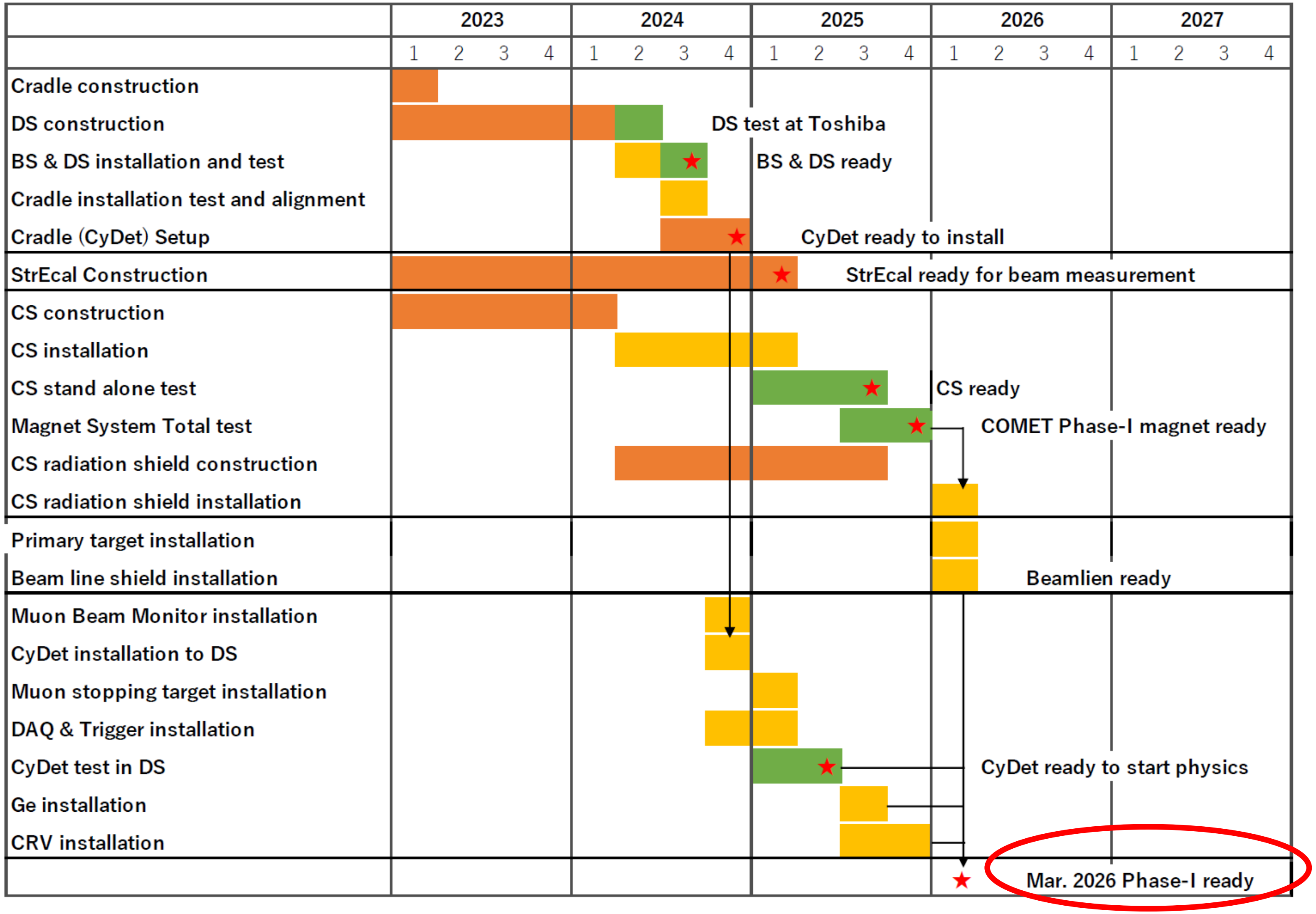
† This estimate is currently limited by computing resources.

Can reach 3×10^{-15} SES in 150 days

The brief status of the Phase-1 preparation

- Magnets
  - Pion Caption Solenoid – almost ready
  - Muon Transport Solenoid – successful commissioning
  - Detector Solenoid – will be made by 2024 spring
- CyDet
  - Drift chamber - equipped with electronics and tested with cosmics
  - Trigger hodoscopes: the design and tests are almost finished
- StrECAl
  - Straw tubes – Plane 1 made and tested with beam, Planes 2&3 in production
  - ECAL – almost all crystals are in hand, mechanical parts ready for mass production
  - Electronics – needs minor modifications before mass production
- Trigger and DAQ - the design is on finish line
- Support Structure - Conceptual design is almost done

The provisional scheduler of Phase-1



Phase-α: the first beam seen by COMET!

- Data taking:

✓ February 2023

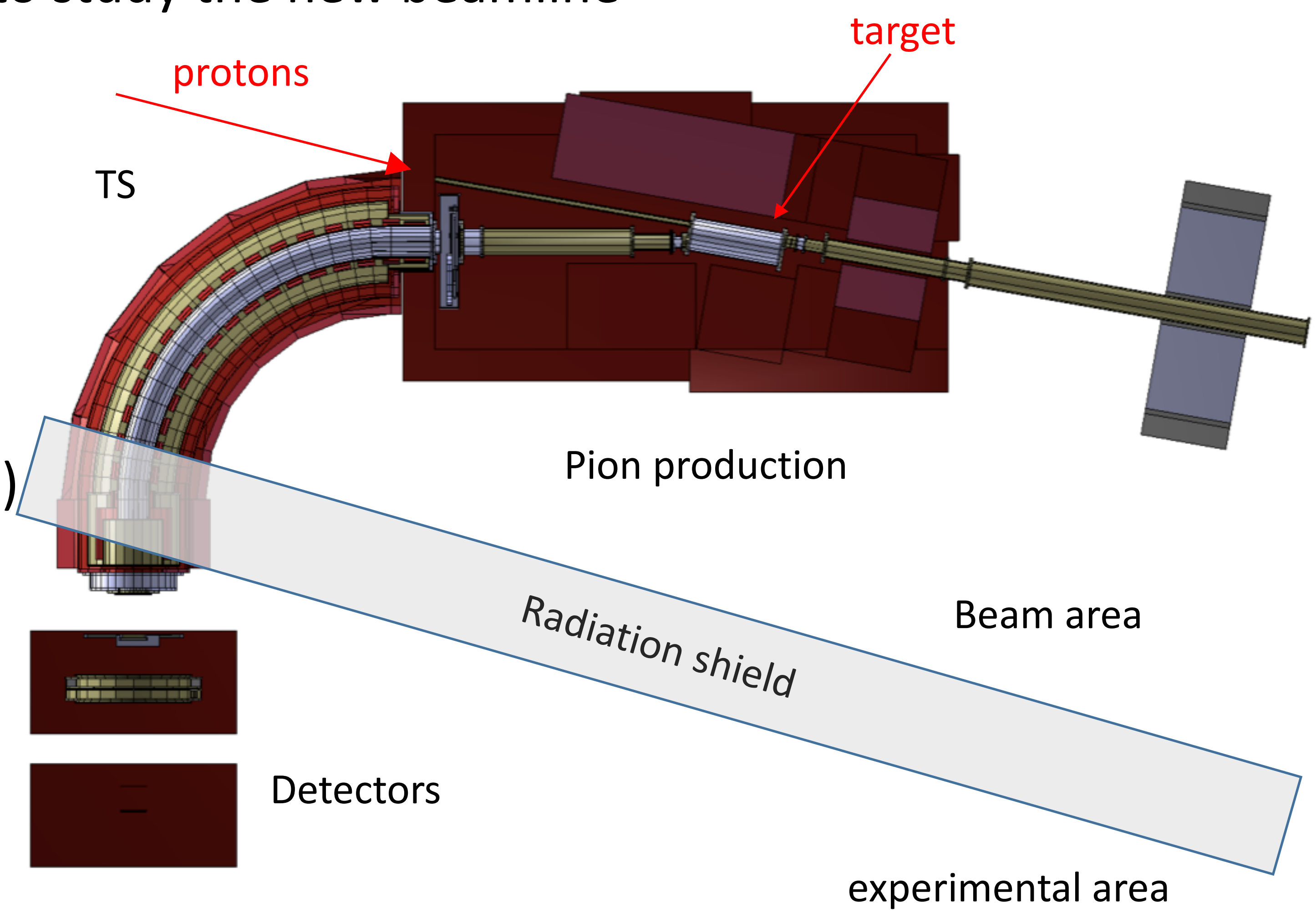
✓ March 2023

❑ Possibly fall 2023?

The Phase-α

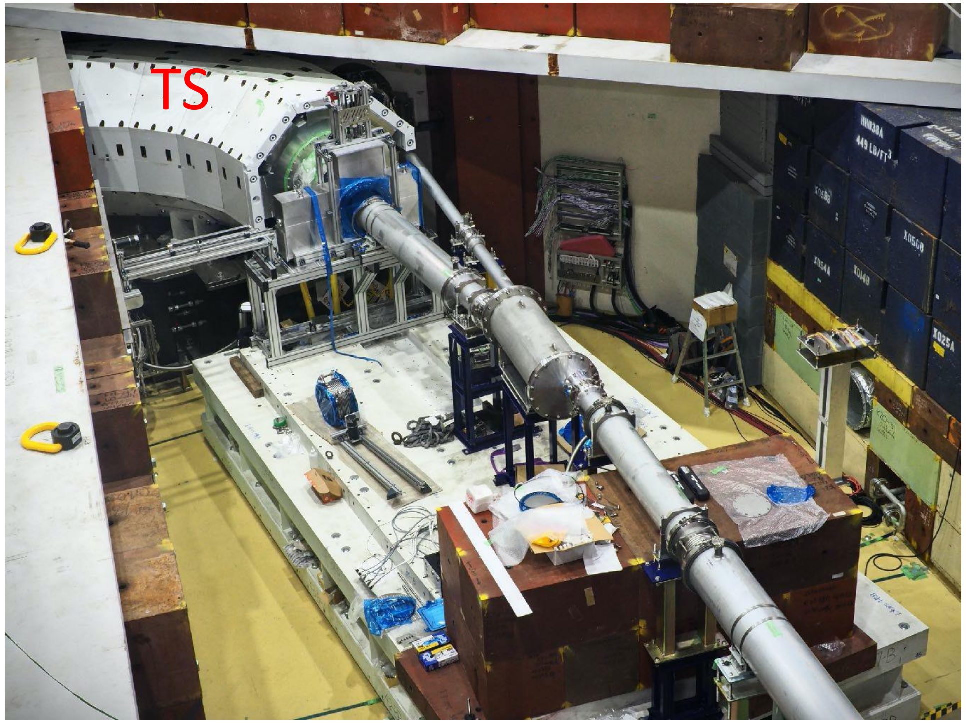
The Goal: Commissioning run to study the new beamline

- Investigation of the secondary beam in the experimental area
- Comparison with simulation and validation of simulation
- Studies of the 90°-curved Muon Transport Solenoid (TS) (operates at 1.5 T solenoidal and 0.05 T dipole fields)

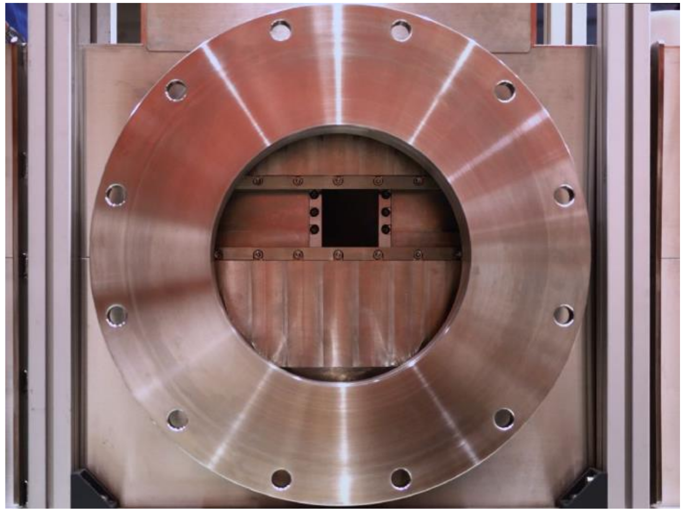


The Phase-α

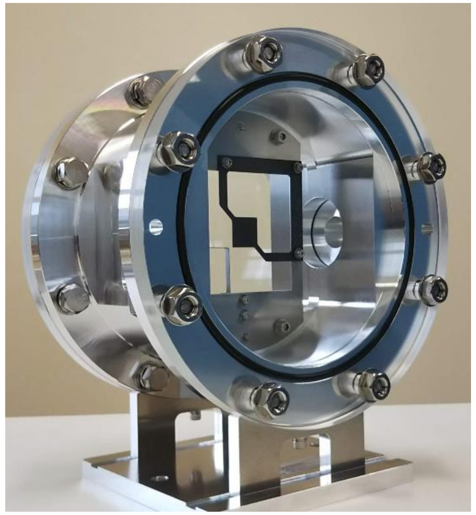
- The simple beamline
- No Pion Capture Solenoid
- 1.1 mm-tick C/C composite Pion Production Target
- The beam mask with two moving collimator slits for study of the transport optics.



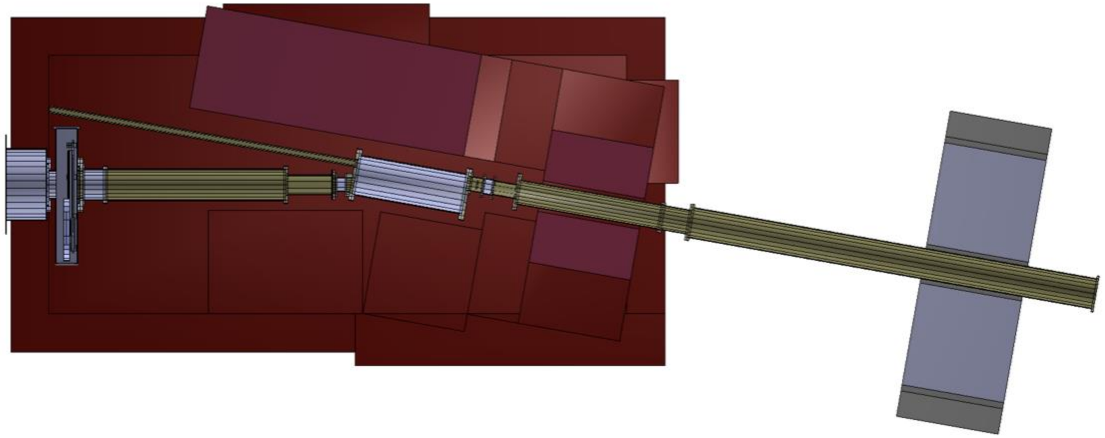
Phase-α Primary Beamline



Beam mask



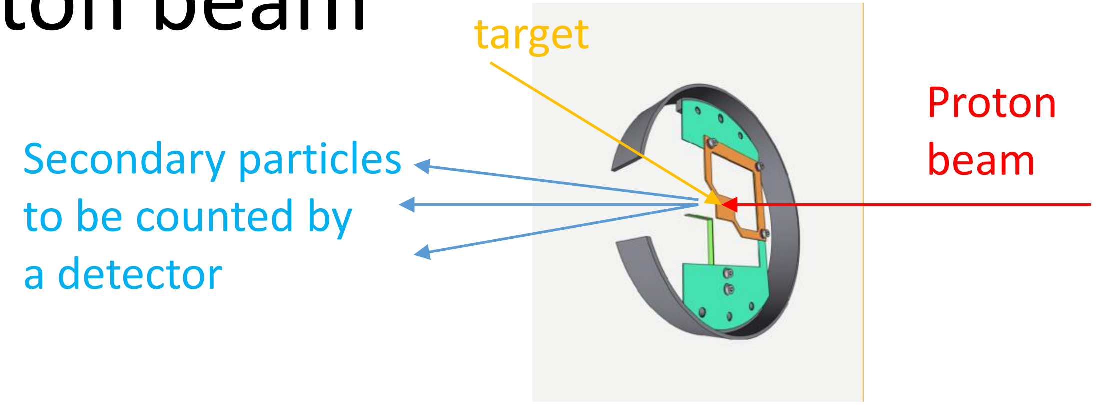
Pion production target

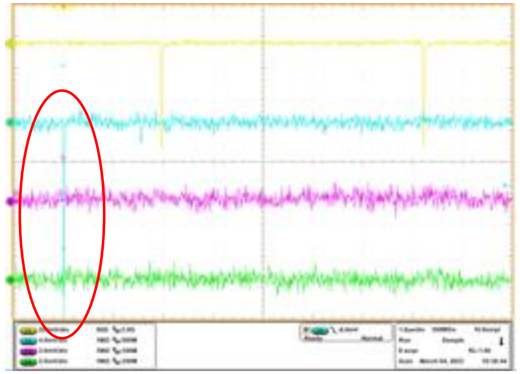


The Phase-α: proton beam

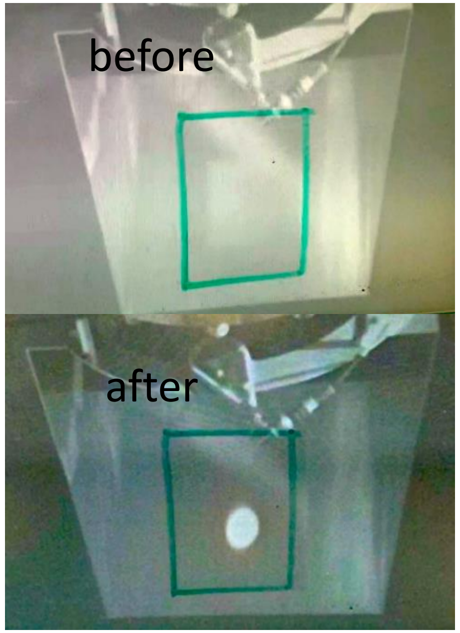
The proton beam successfully extracted!

✦ Slow-extracted & pulsed 8 GeV proton beam at 260 W
★ Beam tuning was well performed
★ Its beam profile was measured
✦ Observed hits on Proton Beam Monitor

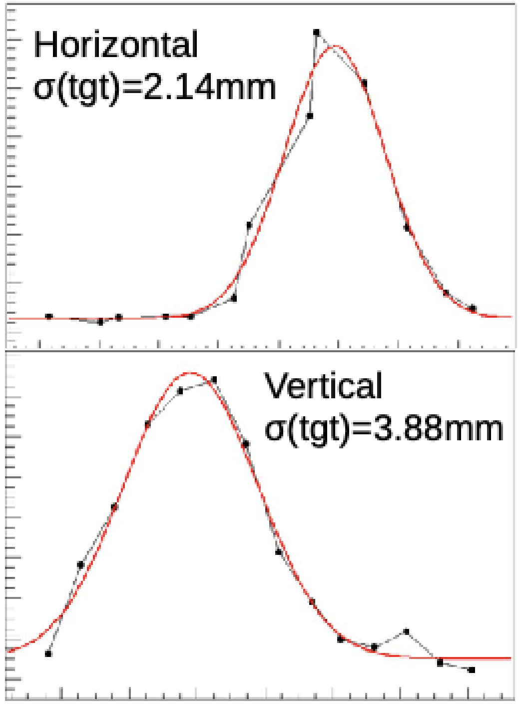




New TiO_2 Sensor for Proton Monitor



Phosphor plate response before and after beam tuning

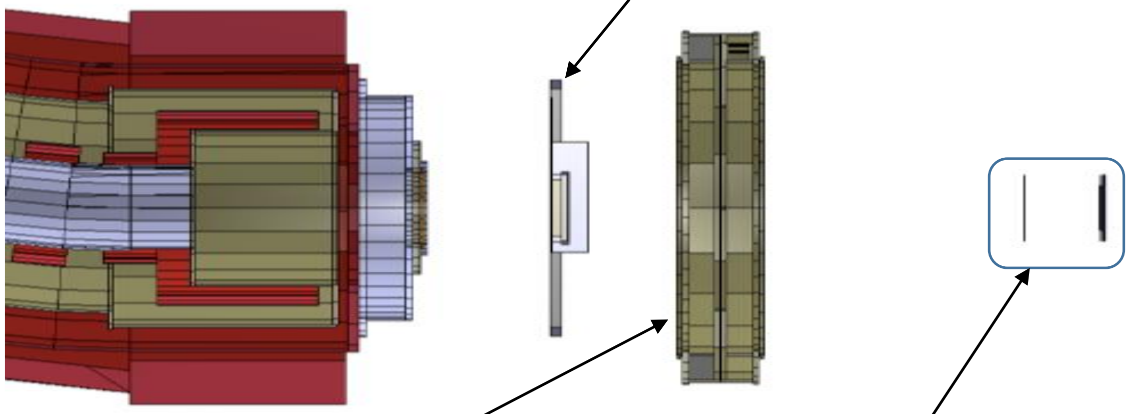


Measured beam dimensions

The Phase-α: detectors

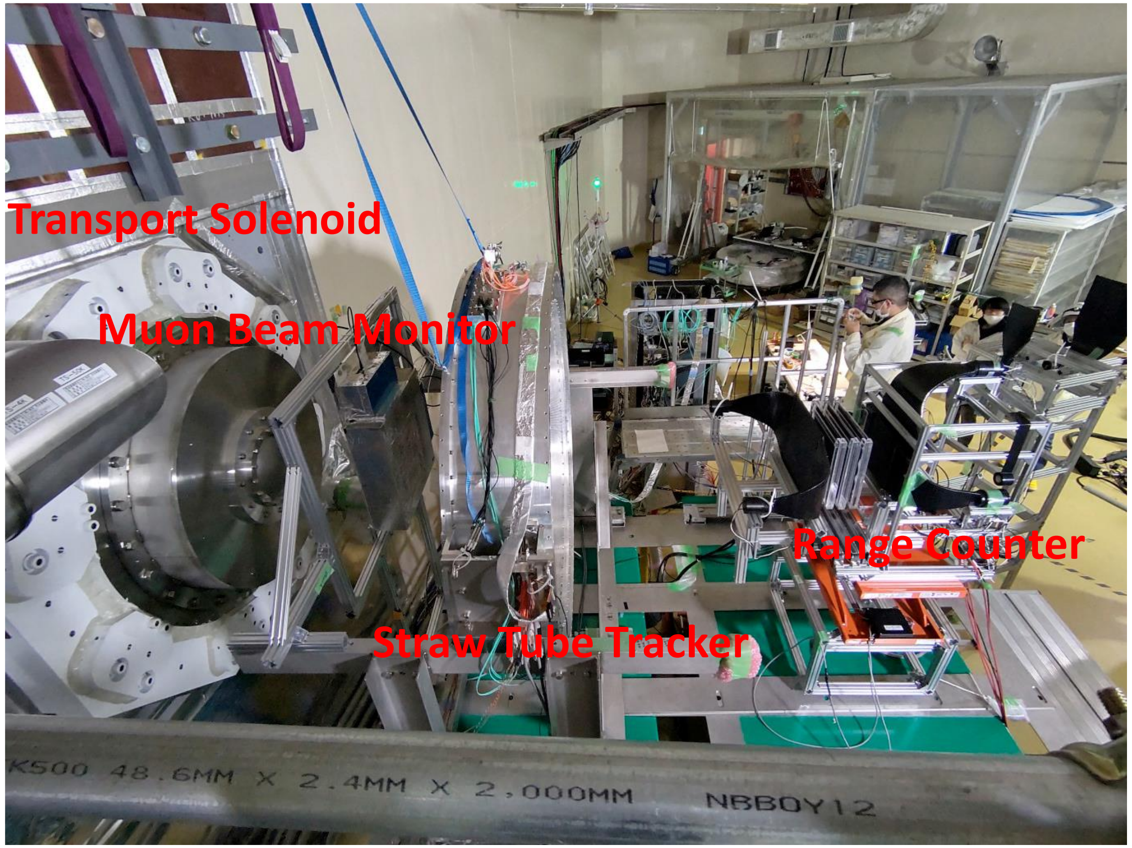
Transport Solenoid

Muon Beam Monitor
Measure beam position



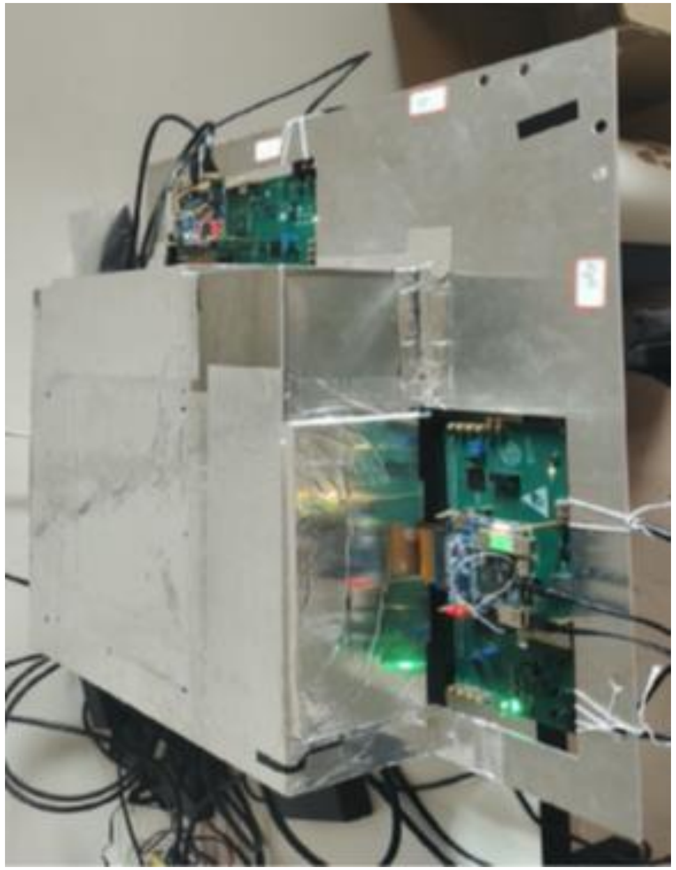
Straw Tube Tracker
Measure beam position
and direction

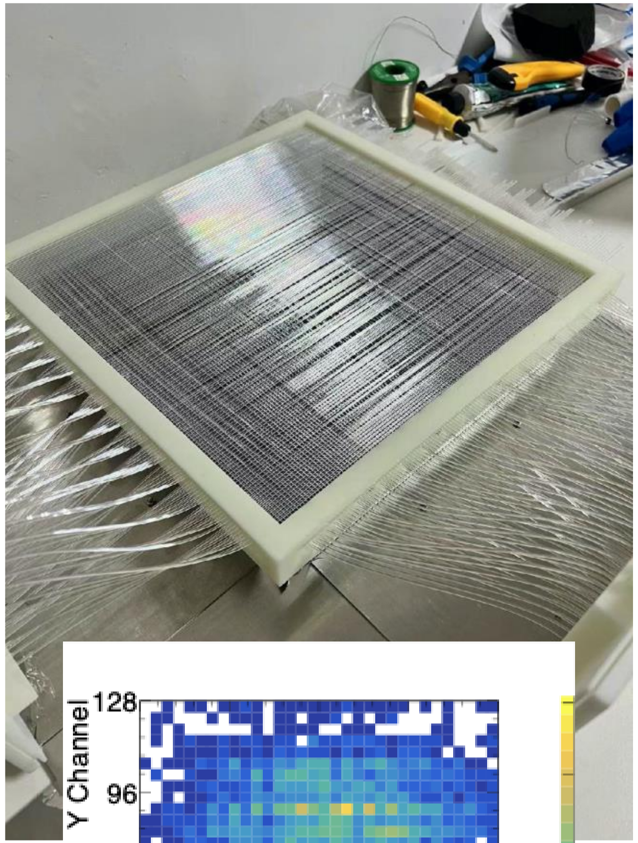
Range Counter
Identify negative
muons and generate
trigger signals.



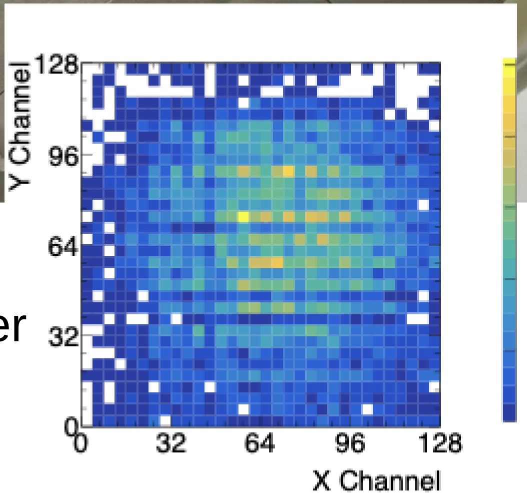
The Phase-α: muon beam monitor

Scintillating fiber hodoscope
Hodoscope detector with 1 mm^2 plastic scintillating fibers
30×30 cm^2 area holds 128+128 fibres aligned to form a plane
readout by SiPMs with dedicated control & readout electronics
3.3 nsec time resolution
Good hit rate tolerance and capability for the experiment.

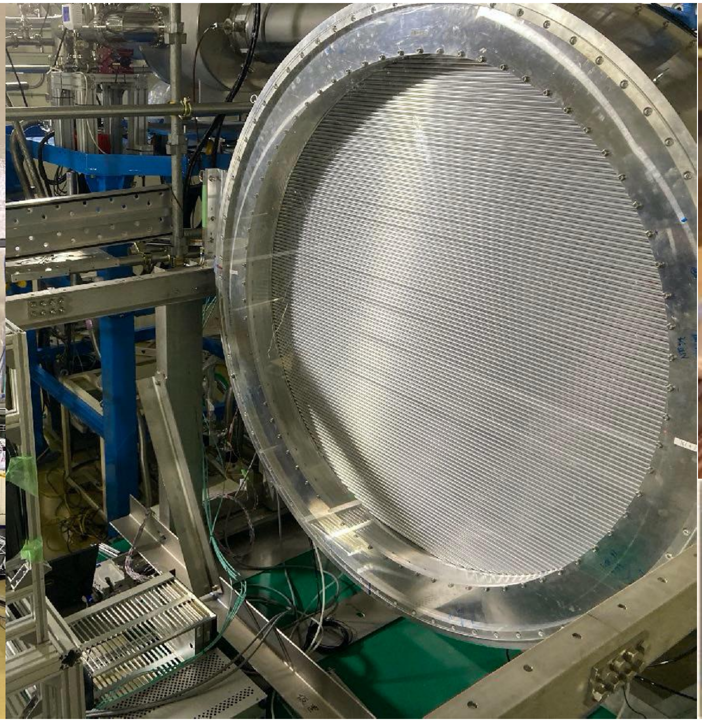




Beam profile associated with trigger



The Phase-α: straw tube tracker

A single Phase-I straw ‘station’ was assembled for Phase-α

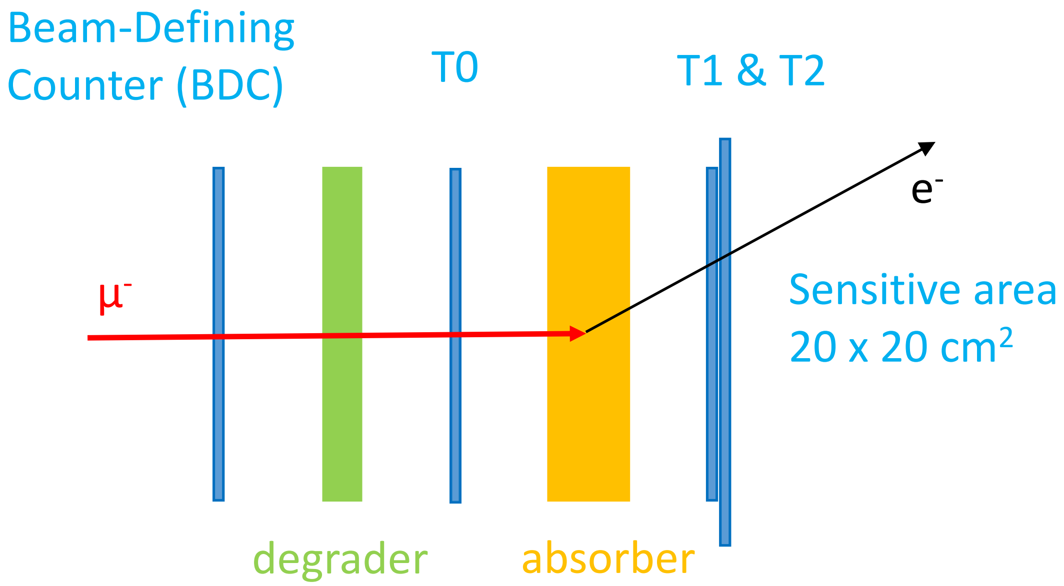
480 straw tubes alined in total on the X & Y axes

Ar & C2H6 (50:50) gas mixture is used

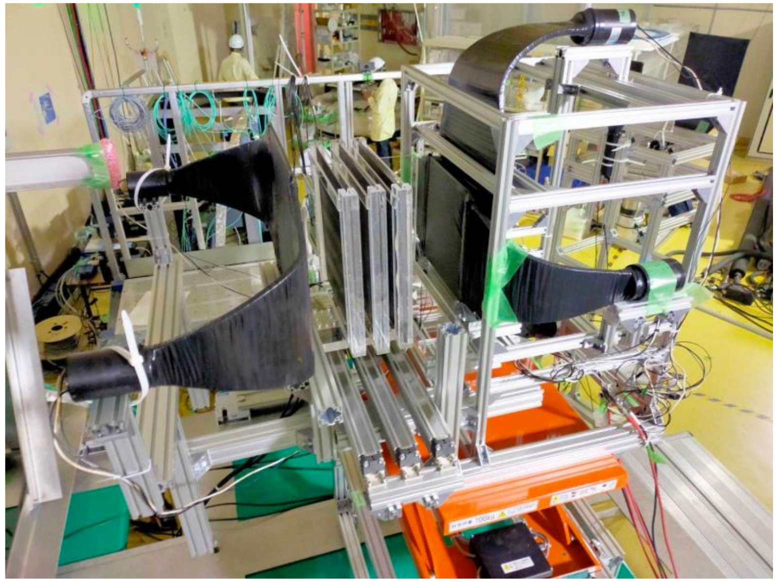
It was the first opportunity for commissioning a Phase-I detector!

Full readout chain was tested

The Phase-α: range counter



(Schematic is not in scale)



Multi-layered plastic scintillating counters measuring muon decay time

Change the momentum range to measure with different thicknesses of a graphite degrader

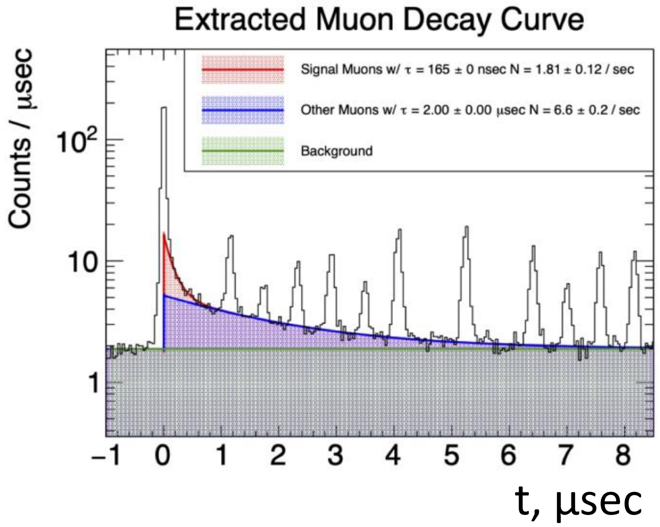
Reconstruct the number of muons stopped in a copper muon stopper

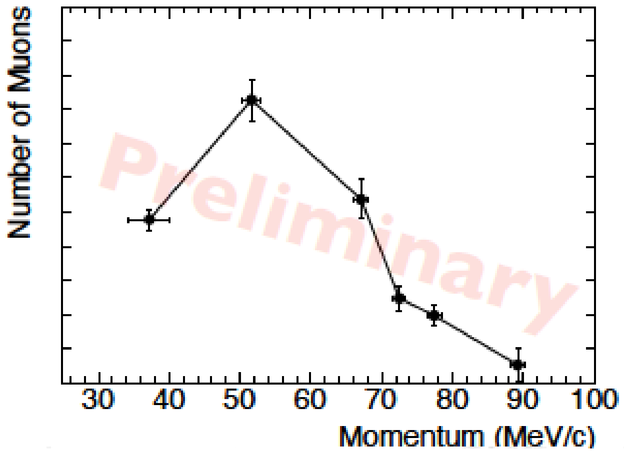
Negative muon's life time in copper is about 160 ns compared to about 2μs in lighter materials

Generated trigger signals when a particle hit *BDC & T0* with no simultaneous hits in *T1 / T2.*

The Phase-α: results

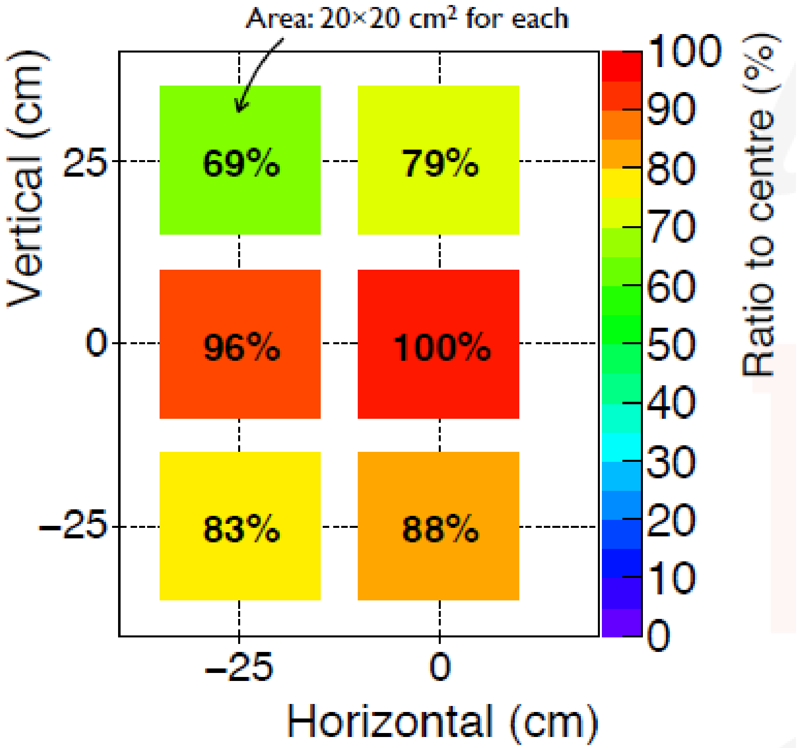
- Negative muons transported via the 90°-curved Transport Solenoid!
- The signal muon decay component was observed
- Reconstructed the number of stopped negative muons counted from the fitted value:
  - only statistical uncertainties plotted
  - the spectrum shape is close to the expectation
- These measurements contribute to the upgrade of the hadron production model studies.
- The reproducing model the data will be chosen for simulation studies for Phase-I & -II.





The Phase-α: Muon beam 2D profile

Seen from downstream



Moved the Range Counter two-dimensionally by 25 cm step.
Muons with a momentum of around 40 MeV/c were measured.
Muons in this momentum range are expected
to concentrate around the center in the vertical direction.

Relative difference of number of muons stopped in the muon stopper among the positions.

Conclusion

- **The Phase-1:**

- preparation is in a good shape but still many issues must be solved
- The goal is to be ready for data taking at March 2026

- **The Phase-α:**

- the first excited data were collected
- data analysis and simulation are in progress

The 2023 is the happy year for COMET!

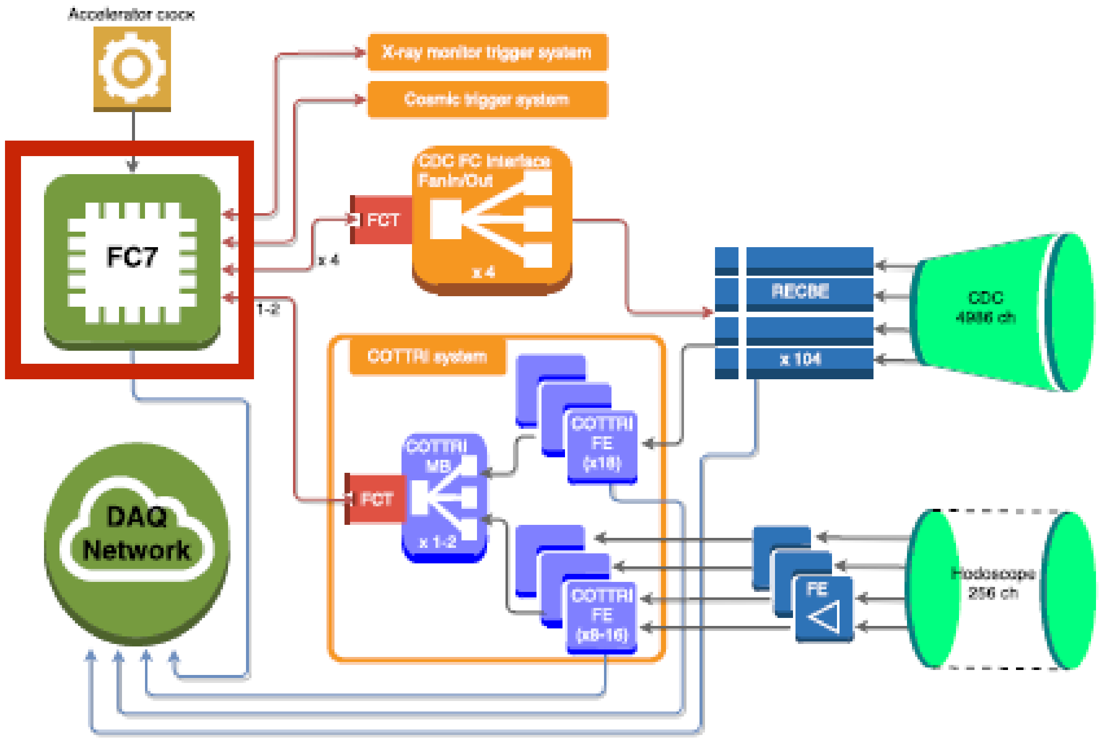
Stay tuning for 2026!

Thanks for your attention!

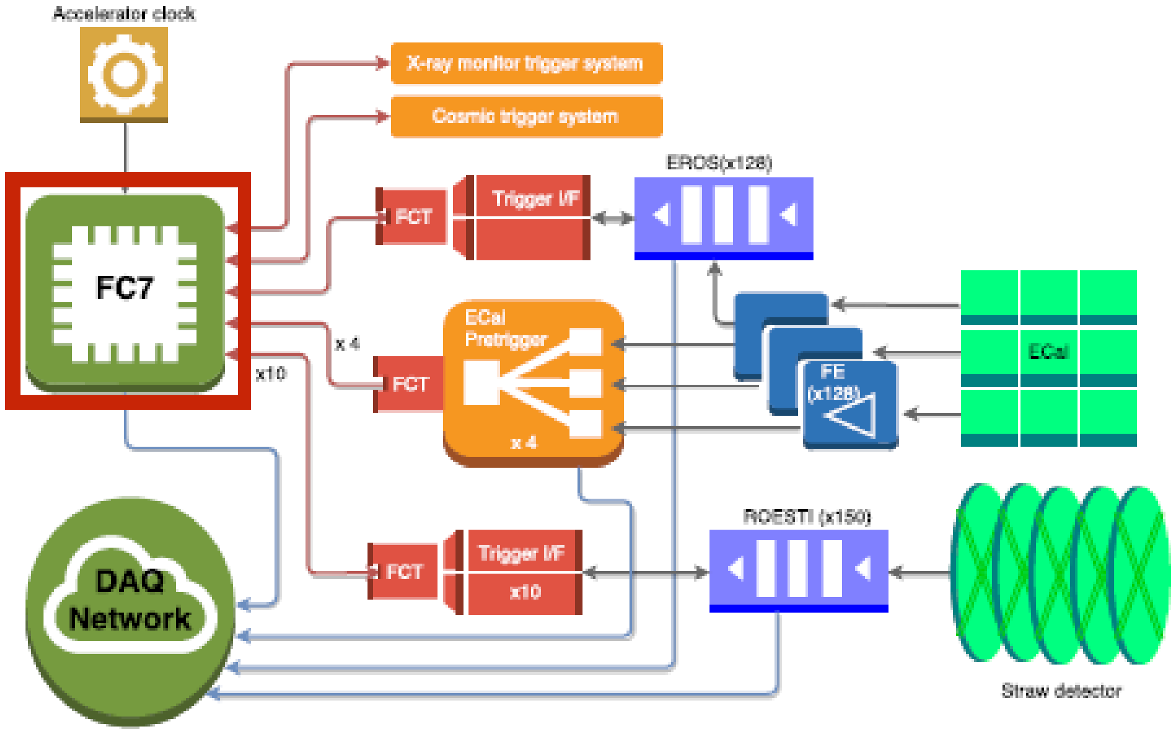
Backup slides

Trigger for Phase-1

CYDET Trigger

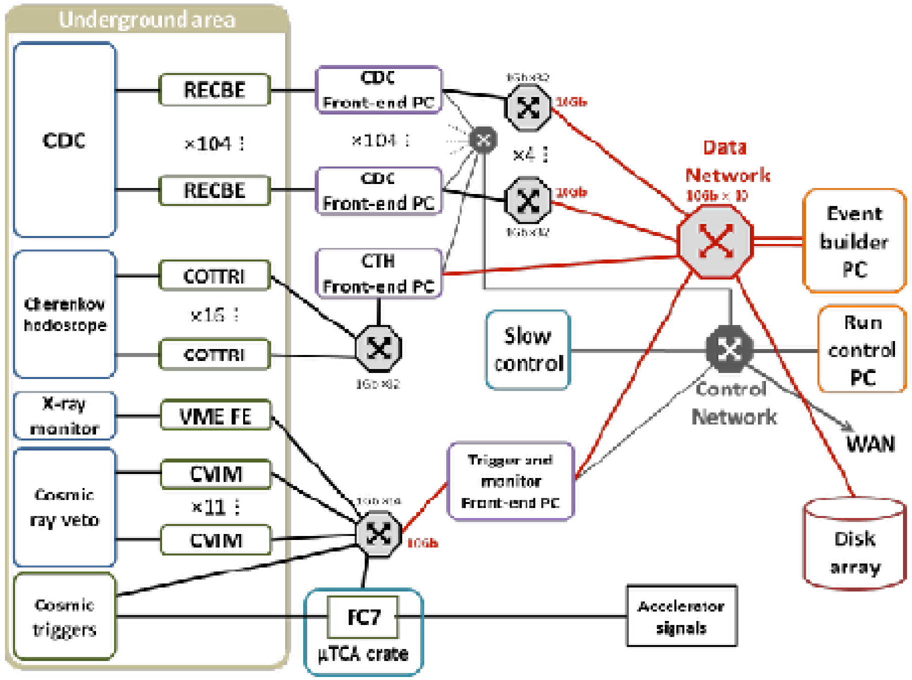


StrECAL Trigger

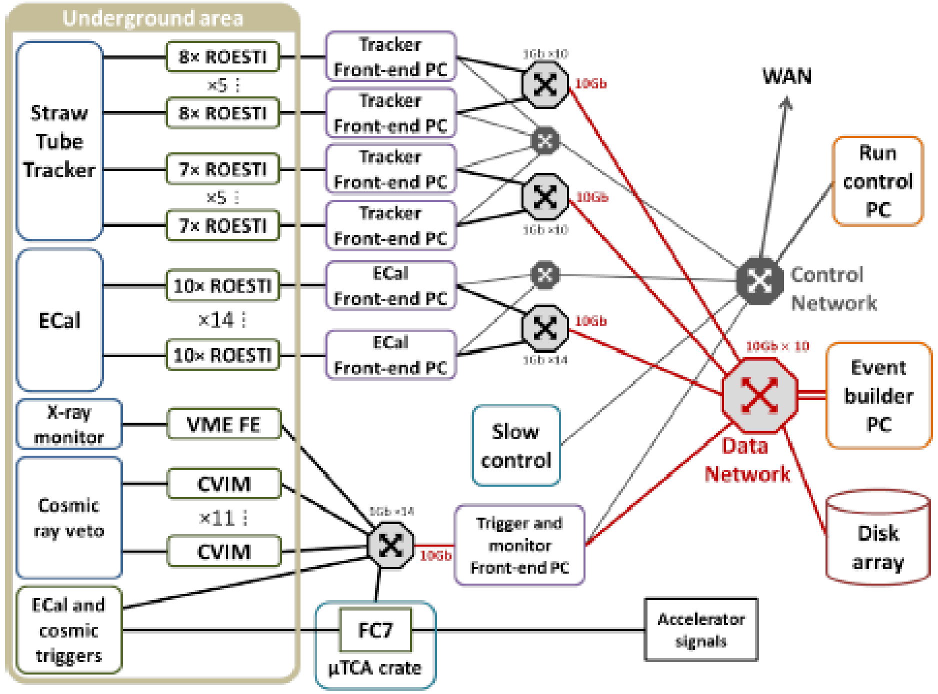


DAQ for Phase-1

CyDet



StrEcal



DAQ is based on standard networking

MIDAS DAQ system for run control

ECAL electronics