Progress of the COMET experiment and Muon program in Japan

Feb.20, 2024

KEK IPNS
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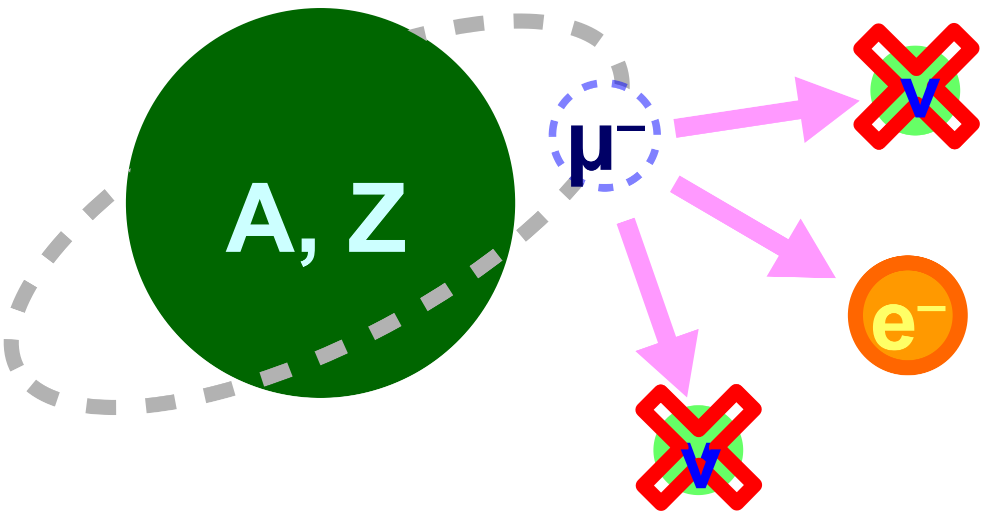
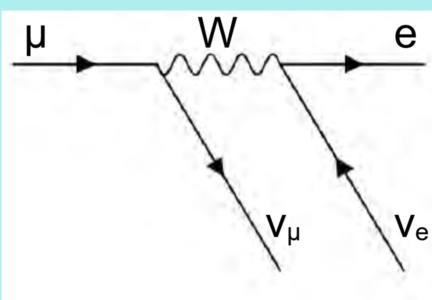
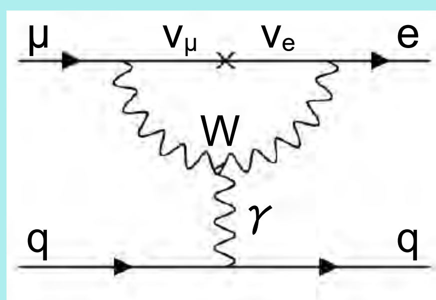
The μ-e Conversion



- Conversion of a muon to an electron is "Charged Lepton Flavor Violation" process and strongly prohibited in the Standard Model.
- Its discovery is an evidence of the new physics.

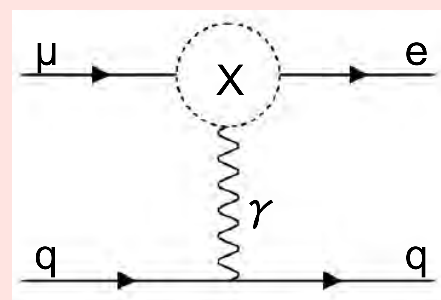
Standard Model

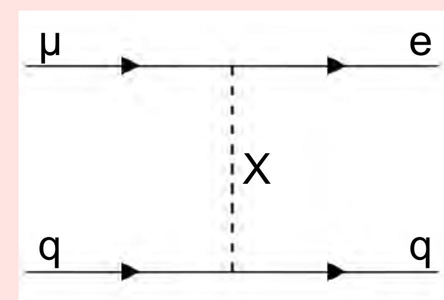




- ✓ Muon can decay to electron with neutrinos.
- ✓ μ-e conversion via neutrino oscillation is <O(10^{-54}).

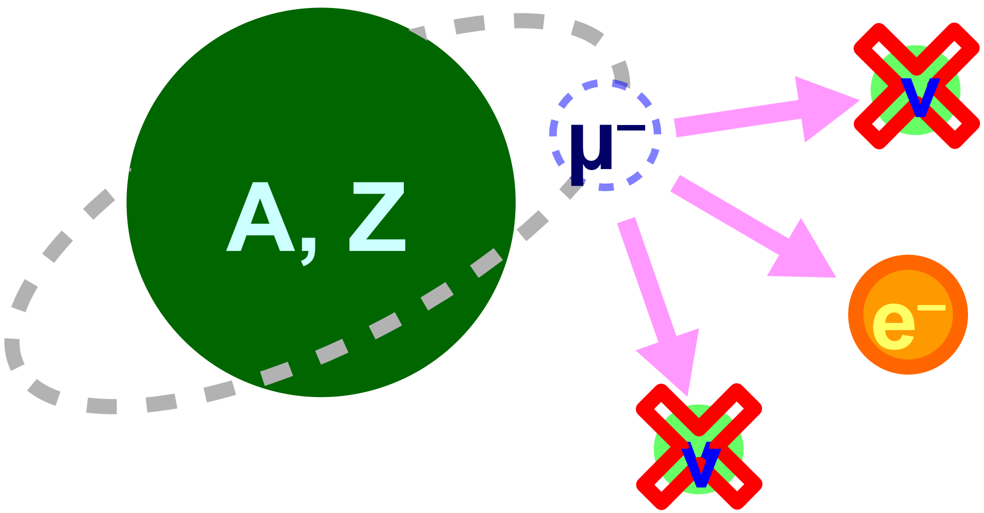
New Physics



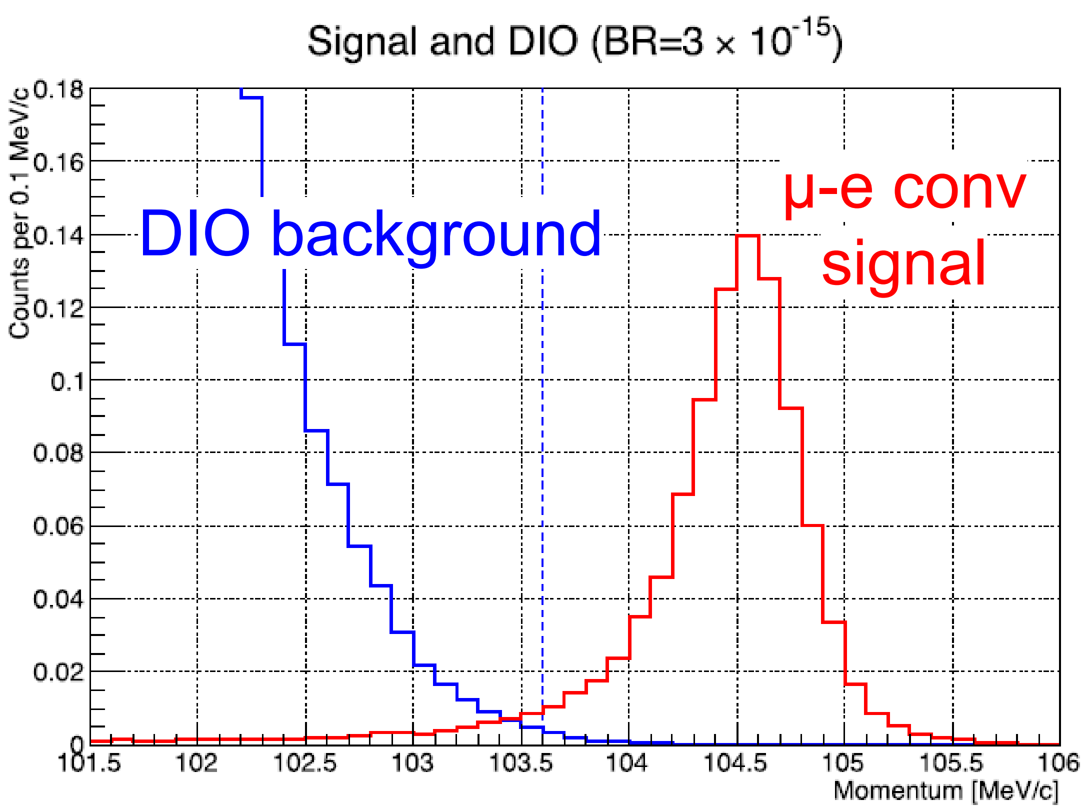


- ✓ Sensitivity for the new physics scale is >1000TeV.
- ✓ μ-e conversion has sensitivity to both photonic and non-photonic interaction.

The μ-e Conversion

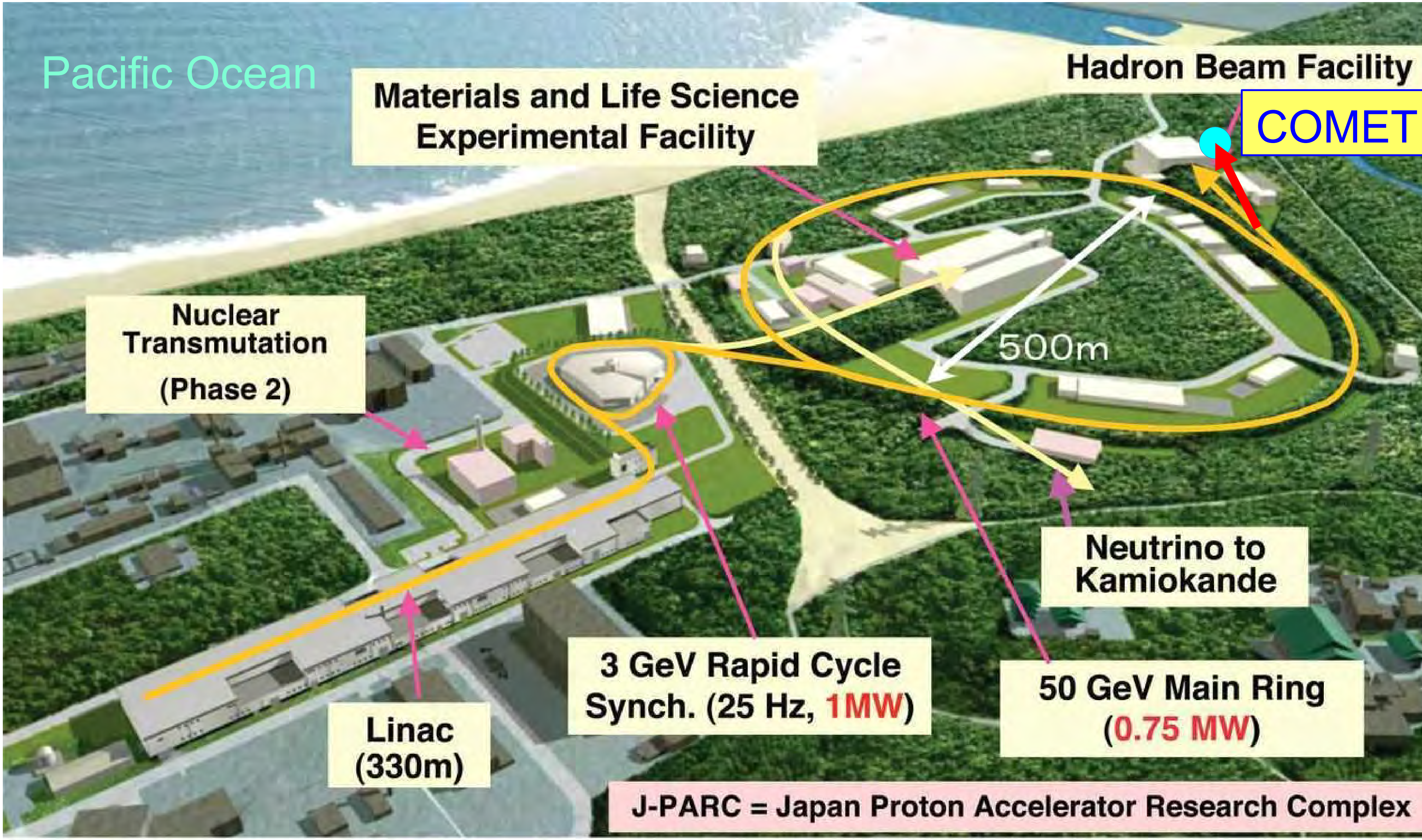


- Current world record of the μ-e conversion is 7×10^{-13} by SINDRUM-II experiment. The COMET experiment aim to reach $O(10^{-17})$ at Phase-II.

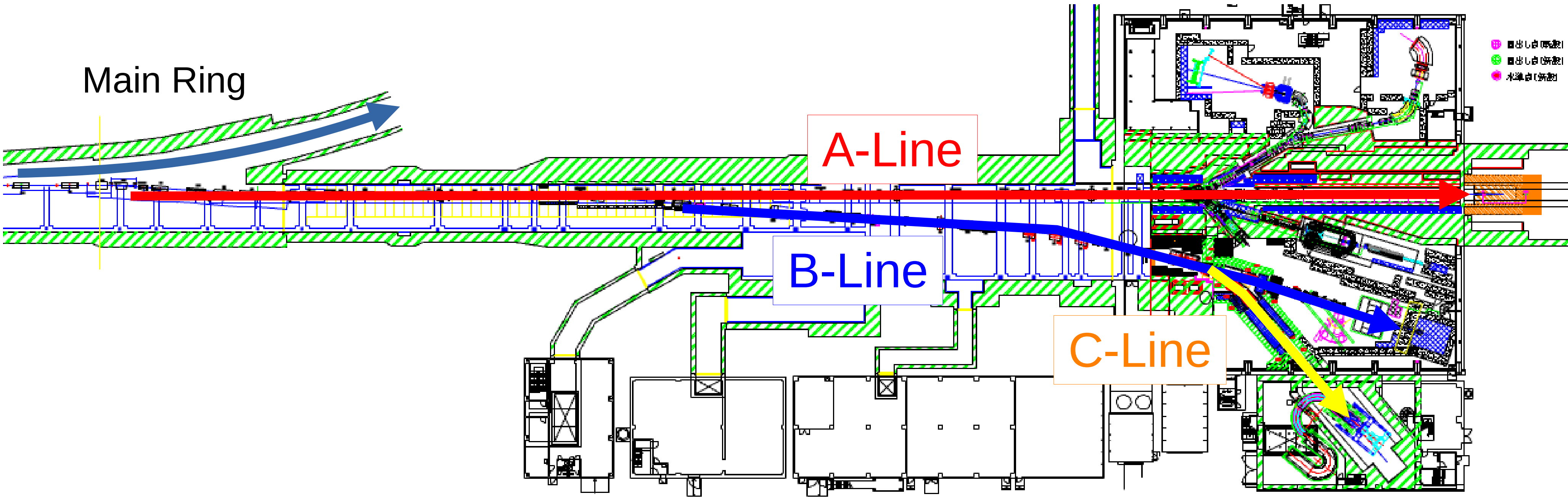


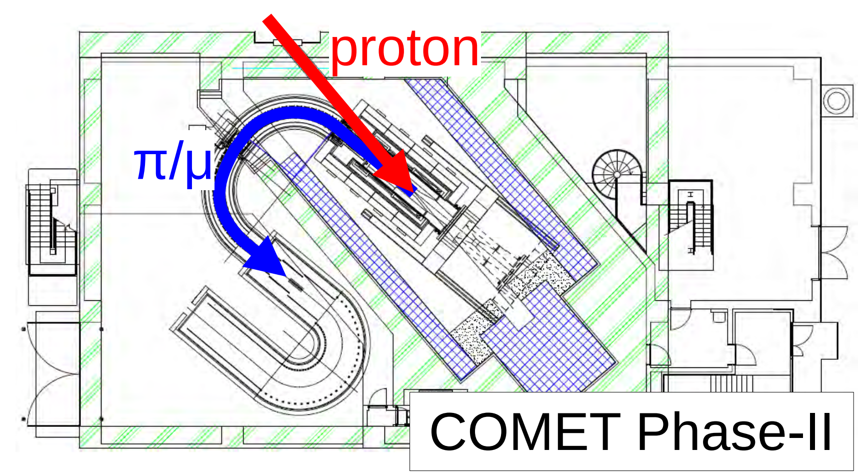
- The signal of μ-e conversion is single electron with energy of about muon mass.
- Electrons from muon decay-in-orbit (DIO) is a major background. It emits a high-energy electron due to recoil of a nucleus.

COMET in J-PARC



Proton Transport Beamline



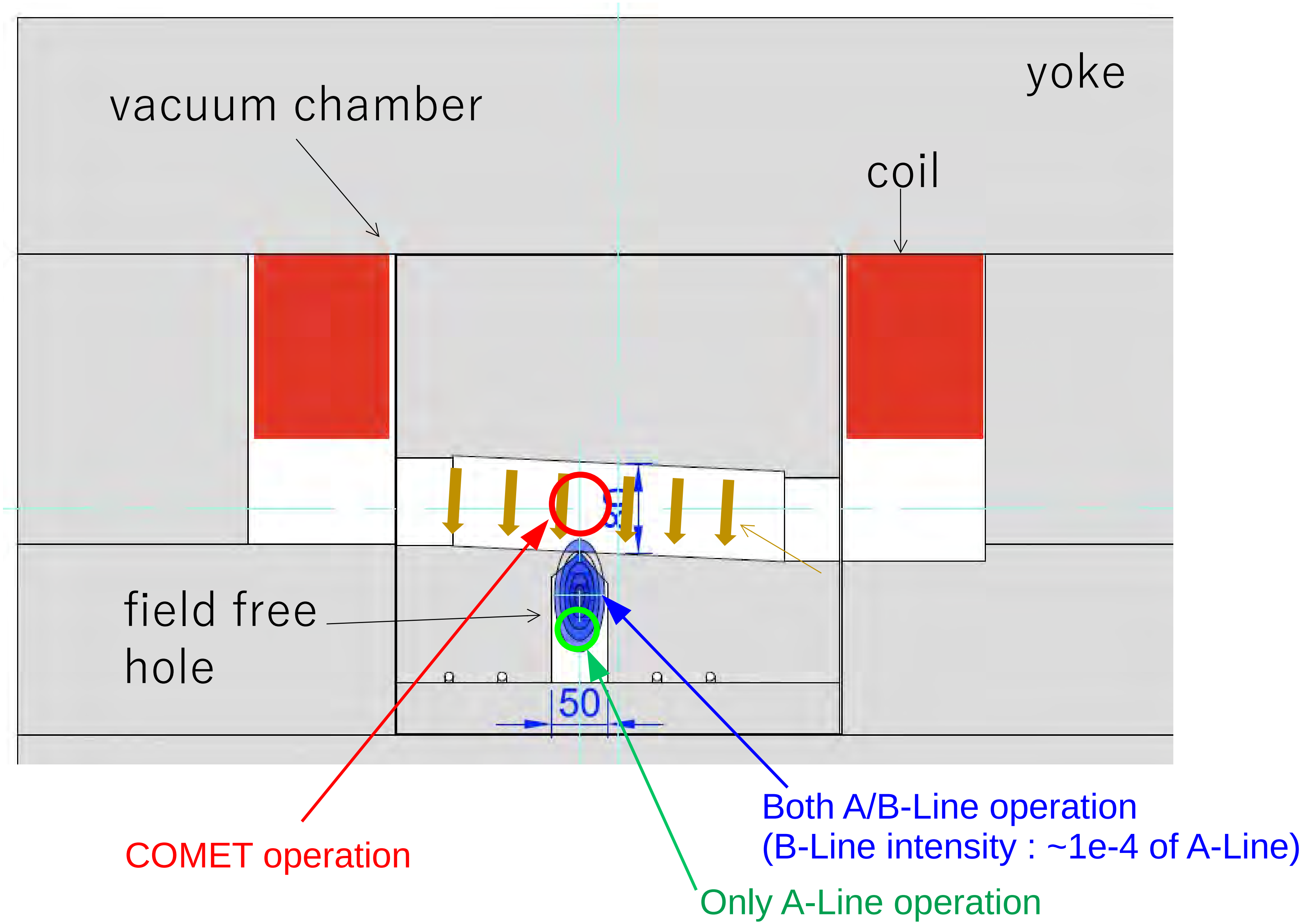


A-Line : Beam is injected to the target to generate secondary beam (π, K, e,,,) and it is provided mainly to the Nuclear Experiment.

B-Line : The proton beam is directly injected to the experimental area. Mass shift experiment is ongoing.

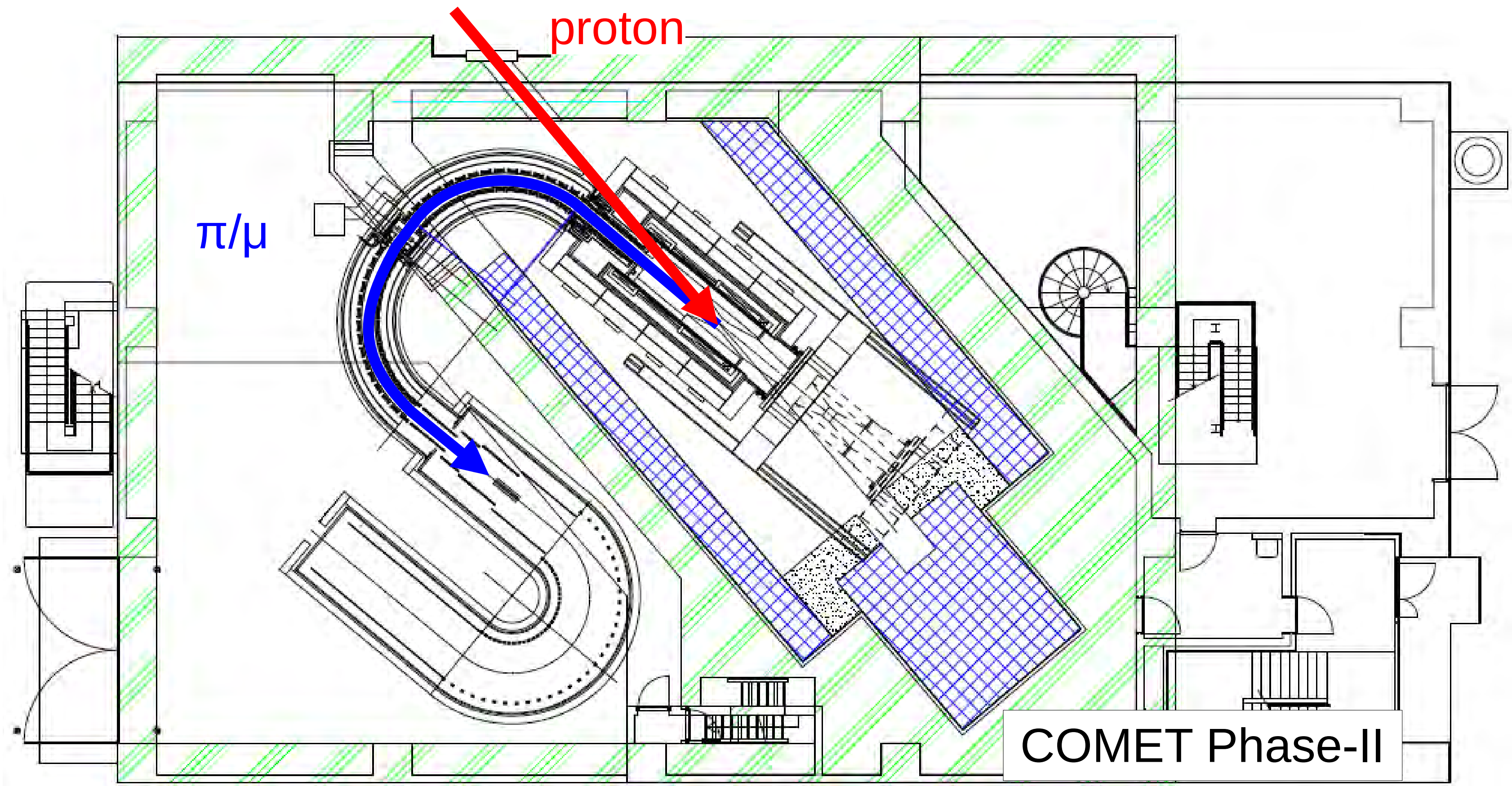
C-Line : 8GeV beam is provided for the COMET experiment.

Lambertson Magnet at Branch of A/B



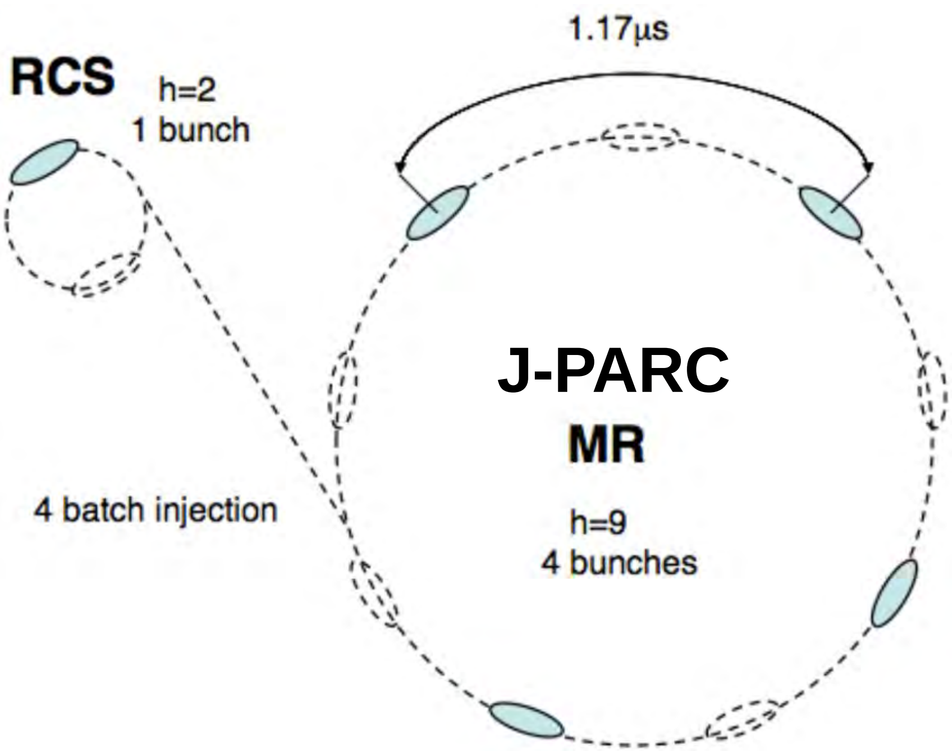
By moving vertical position of the beam, we can change the beam operation mode.

COMET in Hadron Facility

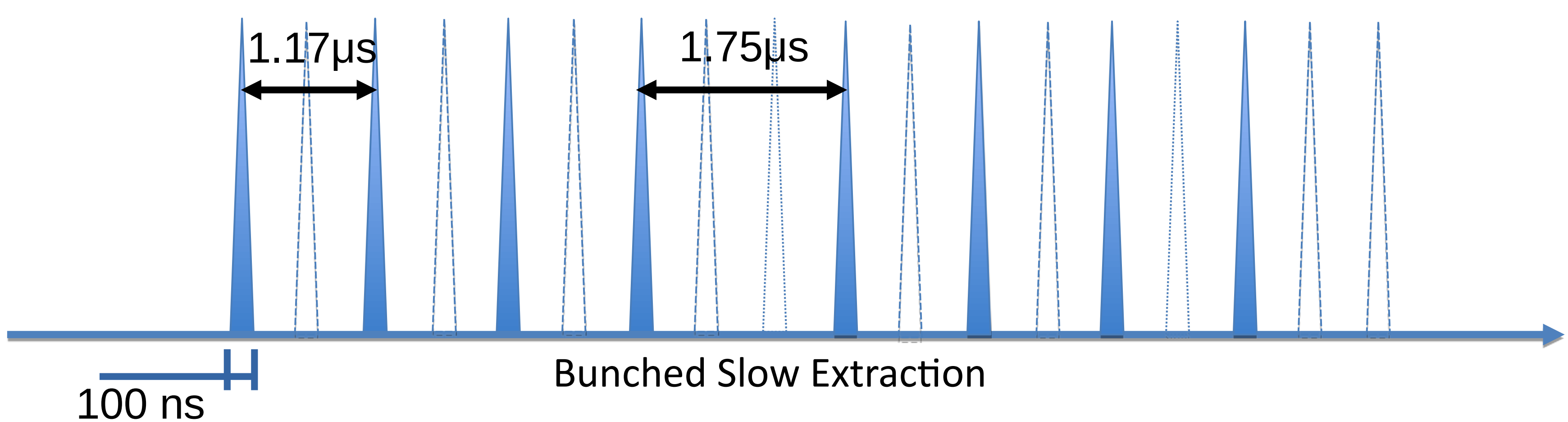


1. J-PARC 8GeV proton beam (56kW max) is injected to the pion production target to generate high-intensity muon beam.
2. Muon beam is stopped at Al target to form muonic atom.
3. Search for high-momentum electrons of the μ-e conversion signal.

Proton Beam Time Structure

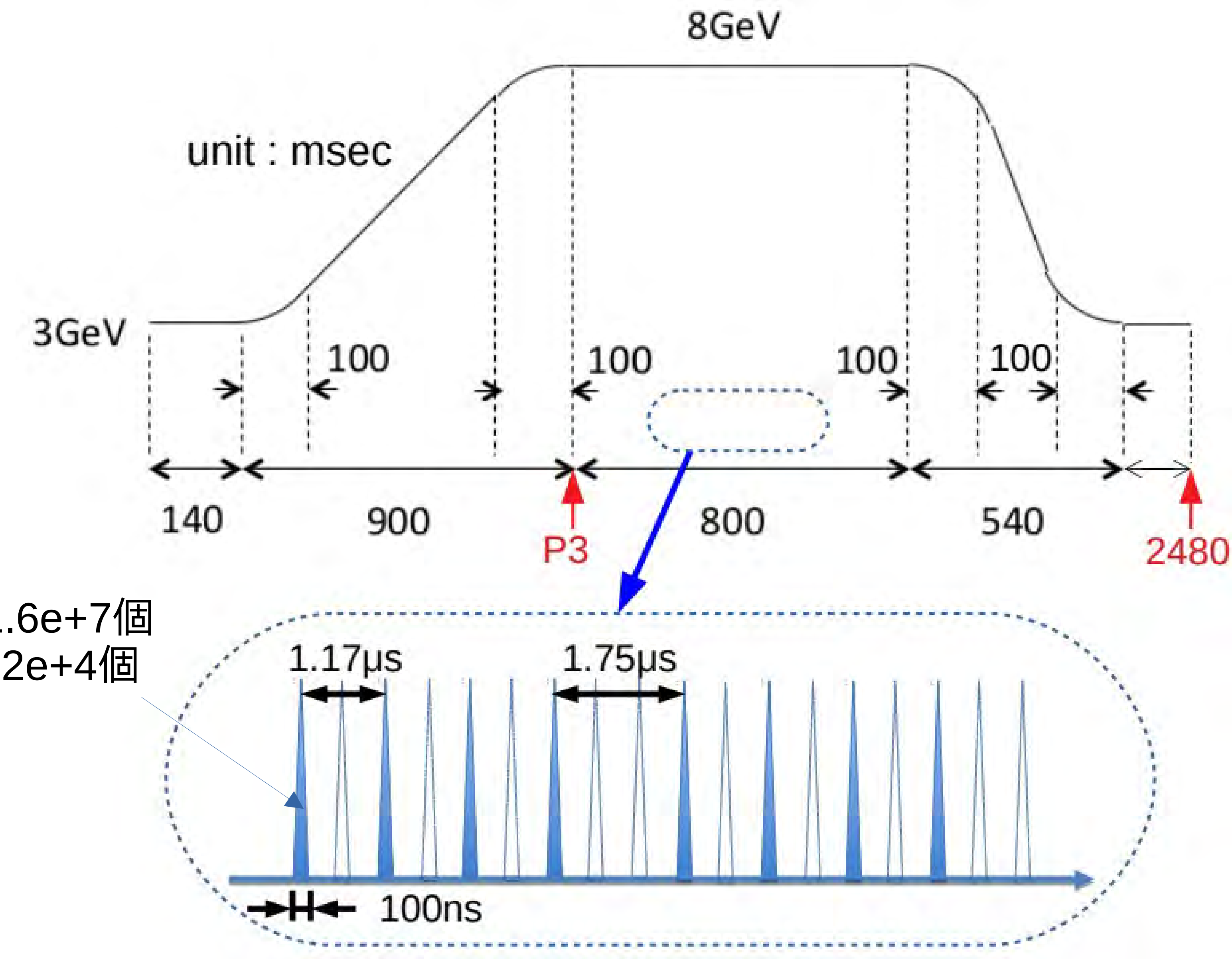


	Phase-1	Phase-2
Energy	8GeV	
Power	3.2 kW	56kW
shot cycle	2.48 sec	(2.48 sec)
proton/bunch proton/shot	1.6×10^{7} 6.2×10^{12}	(2.8×10^{8}) (1.1×10^{14})
muon/bunch	8.2×10^{4}	1.4×10^{6}



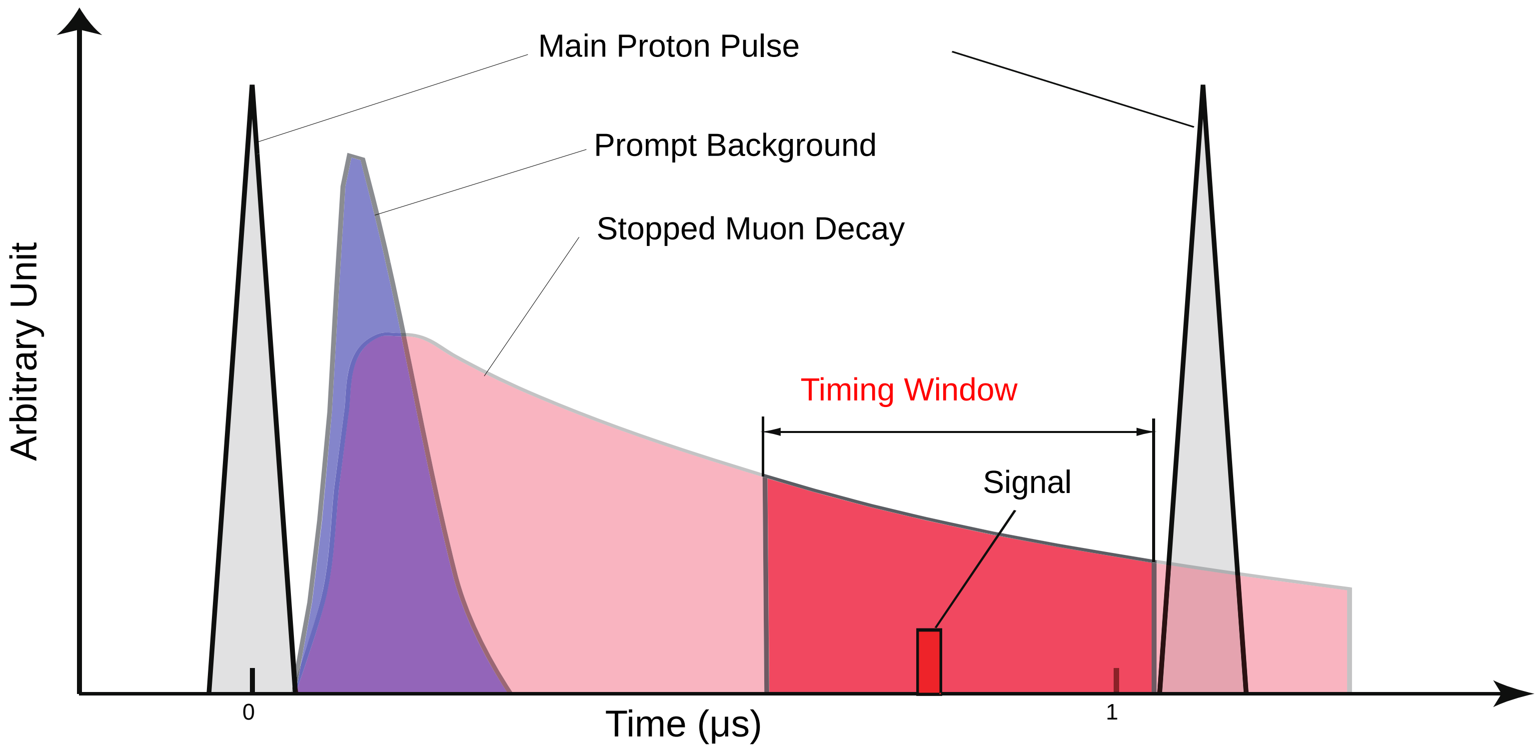
Proton Beam Time Structure

proton：1.6e+7個
muon：8.2e+4個



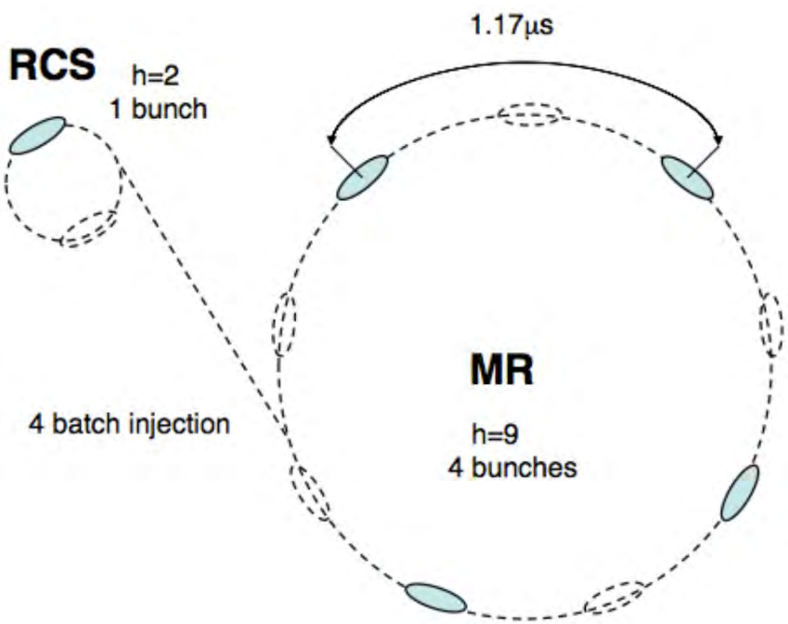
Beam extraction during 0.5 sec

Extinction Measurements (1)

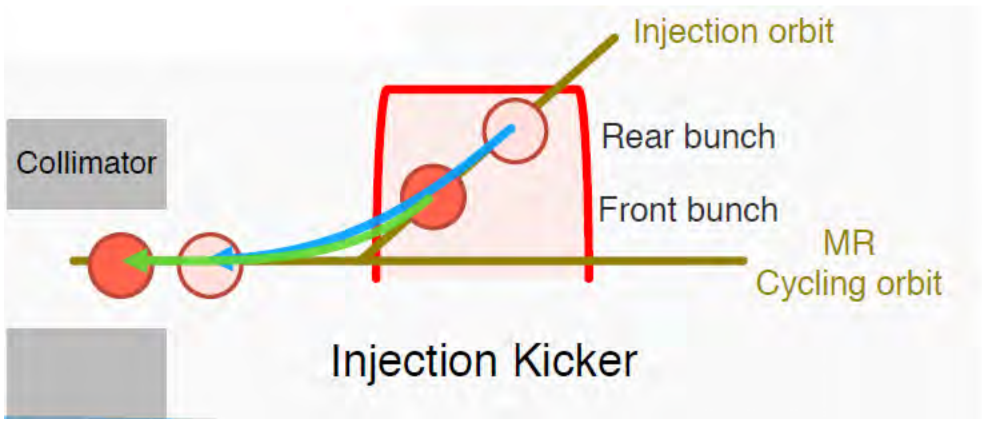


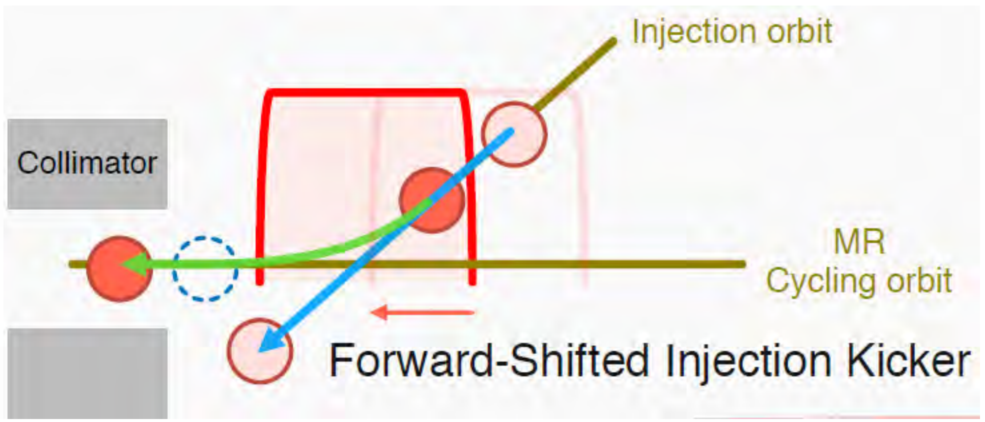
DAQ window is limited between bunches to avoid prompt background.
If protons remains between bunches, it causes background.
Extinction (=remaining proton between beam bunches)
Requirement of extinction is < 1e-10.

How to Improve Extinction



- To realize bunch time structure for COMET, only single bunch is stored in RCS. However, small amount of protons remain in the “empty” bunch.
- By shifting timing of the injection kicker, only filled bunch can be injected to the Main Ring.





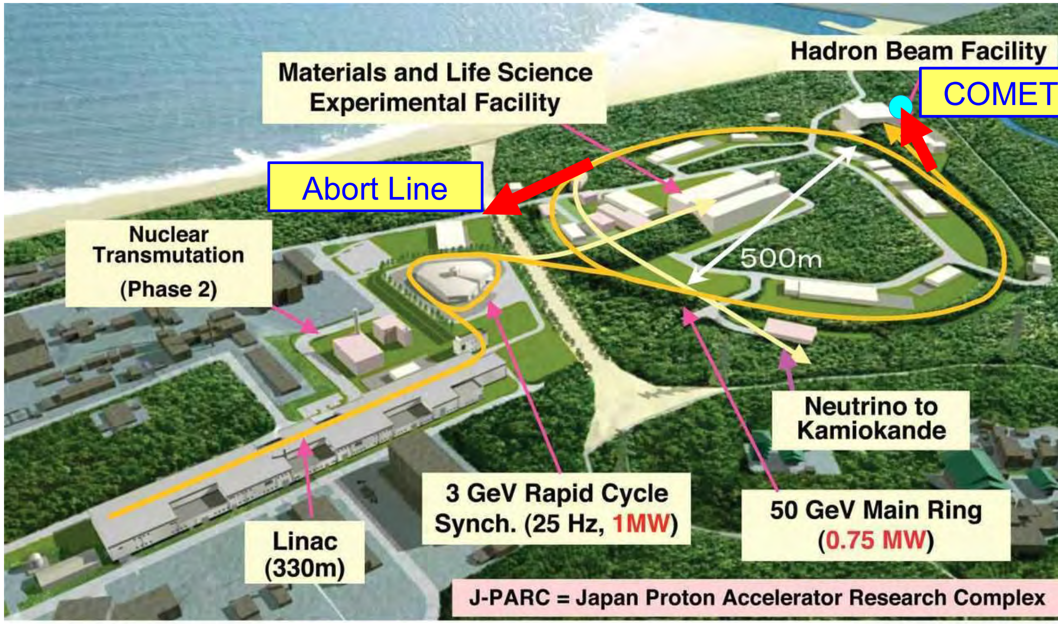
Normal Injection

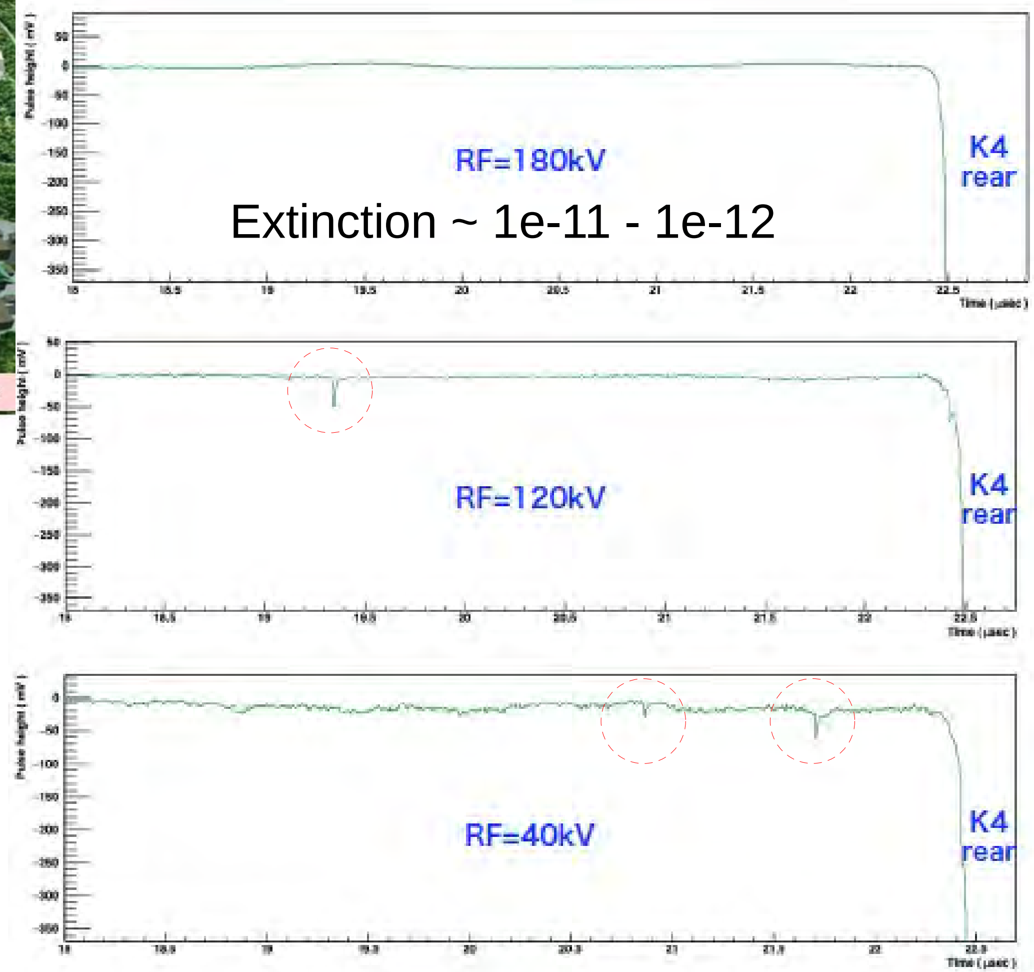
- Both “front” and “rear” buckets are injected to the Main Ring.

Single Bunch Injection

- By shifting kicker timing, only “front” (or “rear”) bucket is injected to the Main Ring.

Extinction Measurements

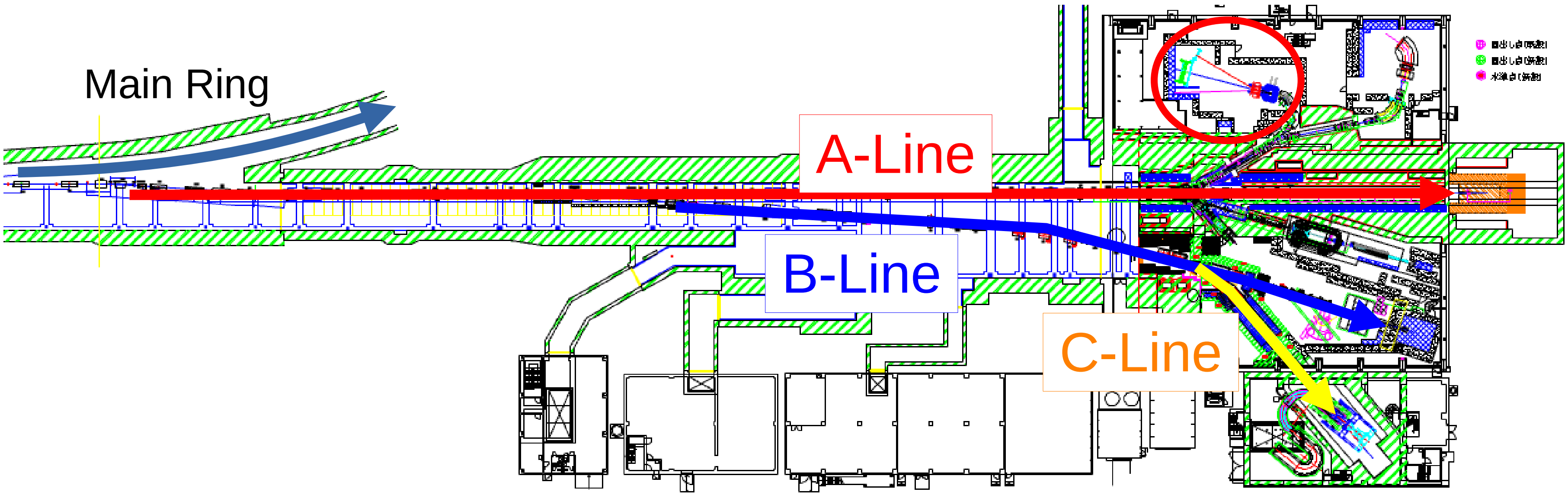


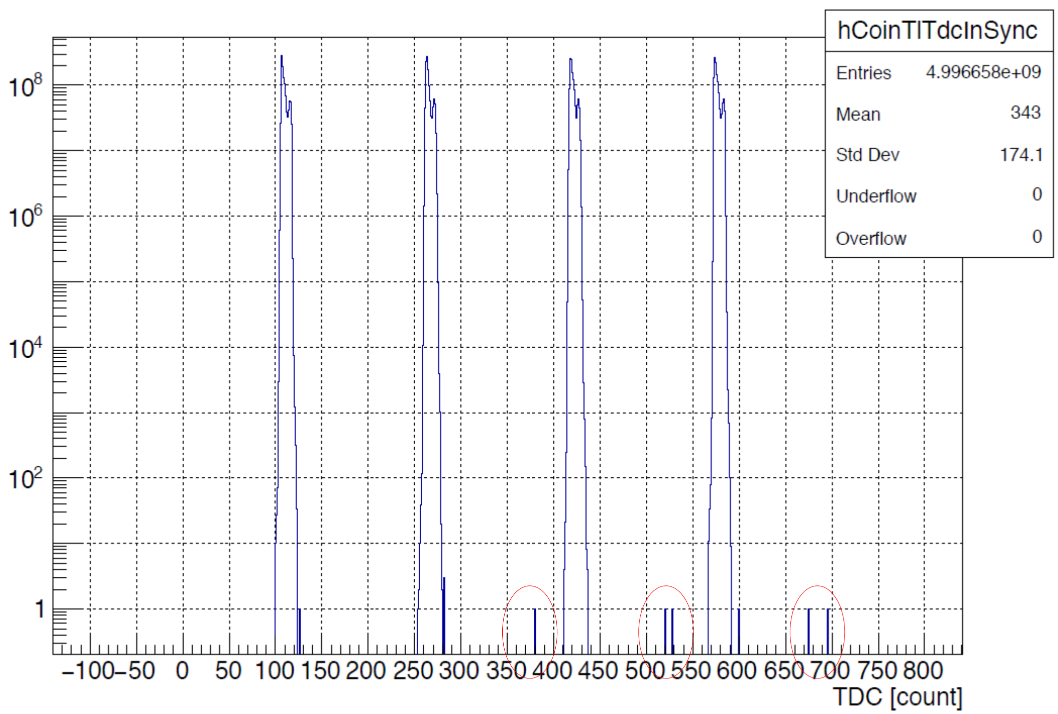


Extinction measurements at MR Abort Line was performed in 2023.

Increasing voltage of RF cavity will reduce the extinction to be sufficient level for the COMET experiment.

Extinction Measurements





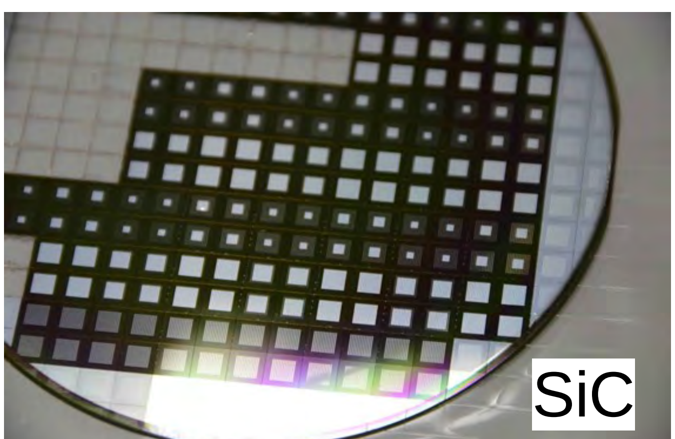
Measurements with secondary beam at K1.8BR area in the Hadron Hall in 2021.

Some extinction were detected but it is likely accidental coincidence of counters.

Extinction < 1e-10

Beam Extinction Monitor

Protons remaining between bunches (Beam Extinction) can generate background in mu-e conversion measurements.
We are trying direct detection of the Extinction.
- The detector must detect single proton.
- The detector should have sufficient radiation tolerance.



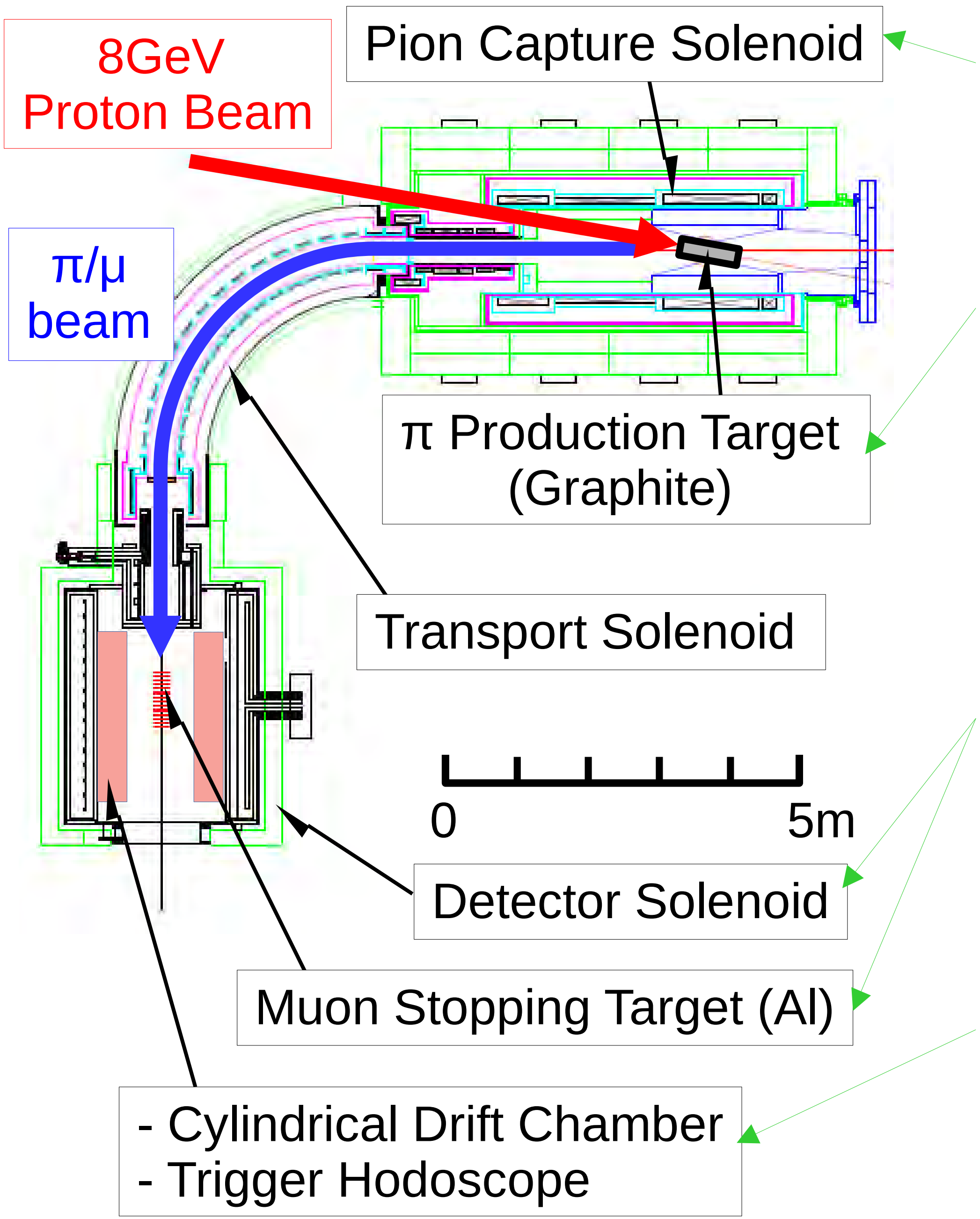
Wide Band-gap Semiconductor Detector

- **Diamond**
  - High radiation tolerance
  - Expensive

- **TiO_2**
  - New technology
  - Cheap

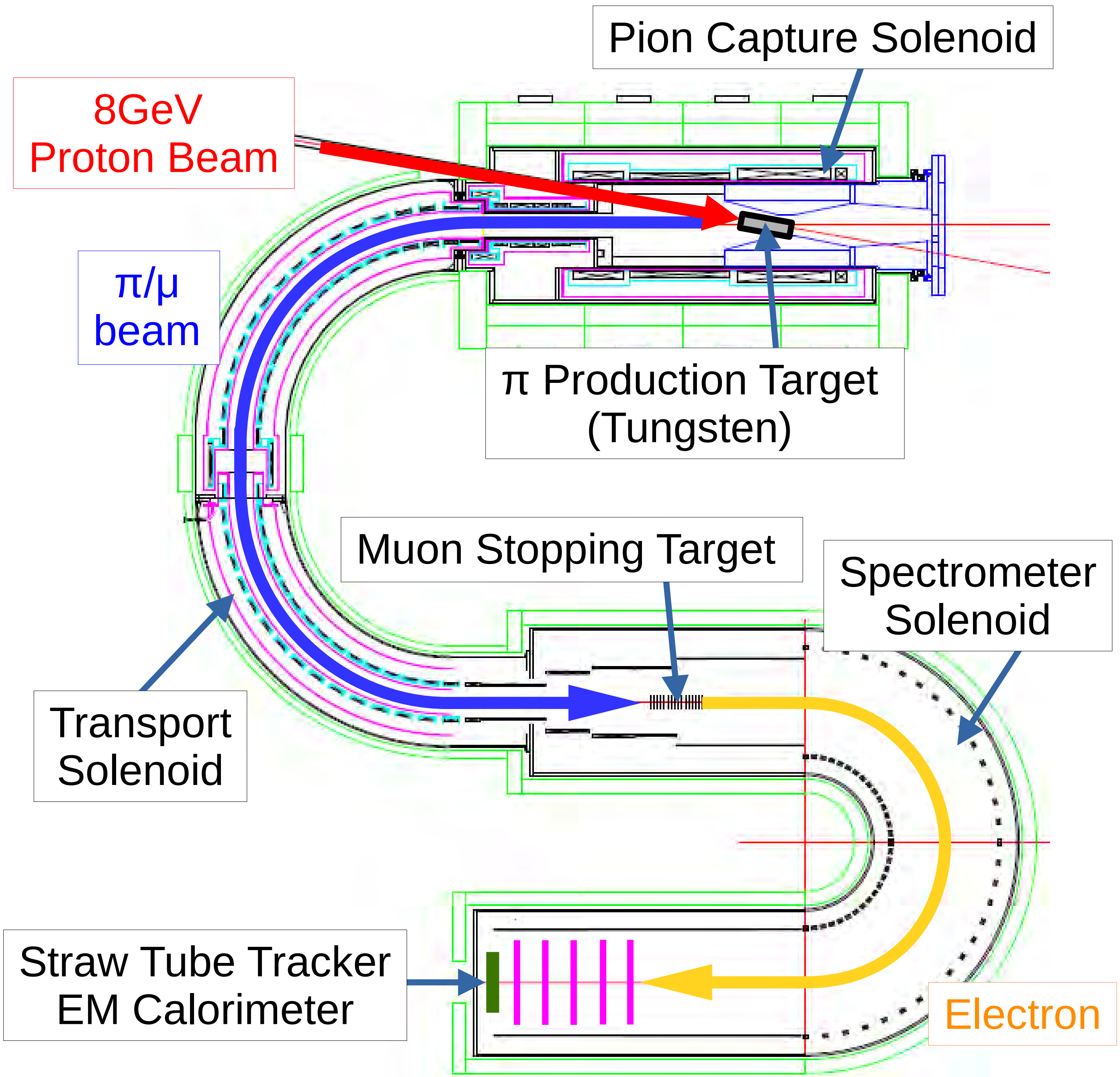
- **SiC**
  - Better radiation tolerance than Si
  - Cheap
  - We are developing muon monitor.

COMET Phase-I



- Pion Capture Solenoid will be installed. It will enhance muon yield by an order of 1000.
- Pion production target will become 700mm long to increase muon yield.
- Expected sensitivity at COMET Phase-I is 7×10^{-15}.
- Detector Solenoid and aluminum muon stopping target will be installed to measure momentum of decay electrons.
- Main detector at Phase-I is Cylindrical Drift Chamber.

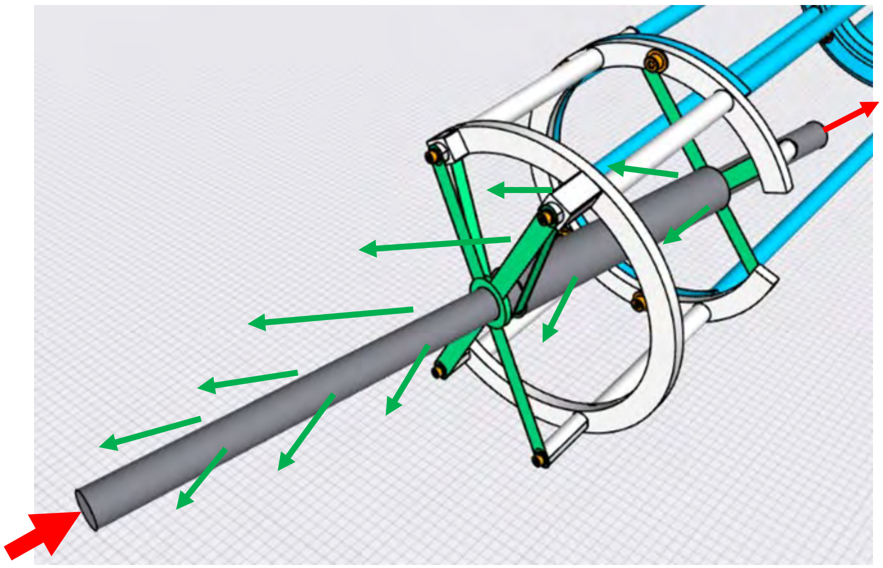
COMET Phase-II : Final Setup

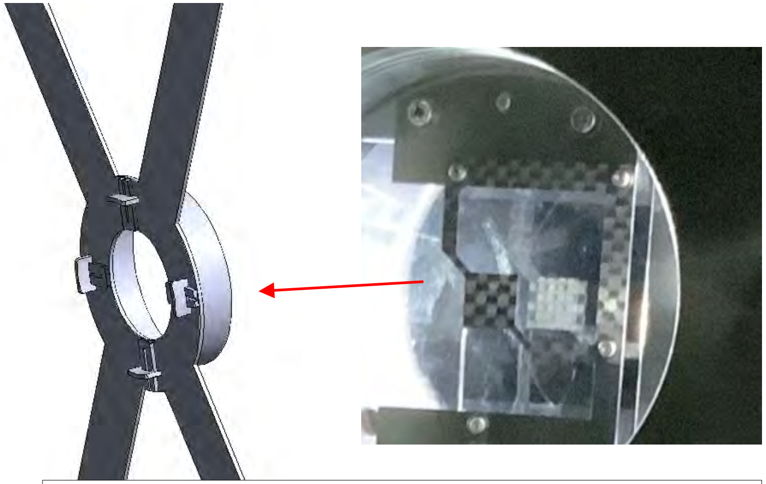


After Phase-I completed, significant upgrade is planned to achieve further sensitivity of a factor of 100.

1. Proton beam intensity will become 20 times higher.
2. Production target will be replaced to tungsten.
3. Transport Solenoid will be extended twice longer.
4. Electron spectrometer will be installed.
5. Straw tube tracker with EM calorimeter will be installed.

Graphite Target @ Phase-1





Manufacturing of target support by C/C composite

The objective is to collect as many muons as possible.

Graphite rod, L=700 mm, is floating on the center of superconducting solenoid magnet.

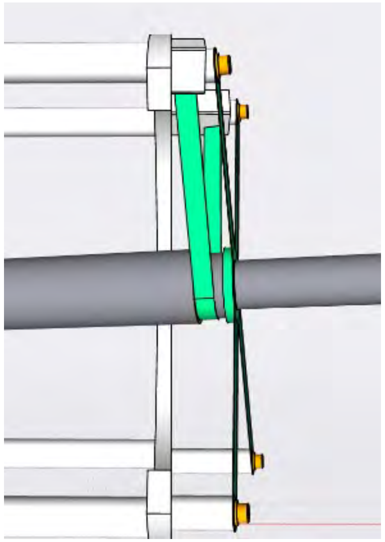
<u>Target support</u>

- Should not disturb the pion transport
- Will be irradiated by proton beam

<u>Material & Structure</u>

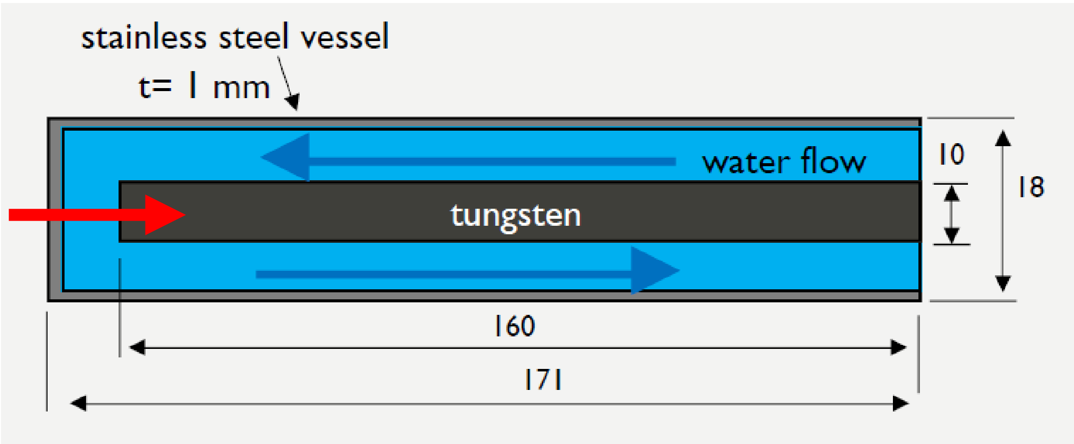
- Refractory material
- Not-bulk material
- Low-density is preferable

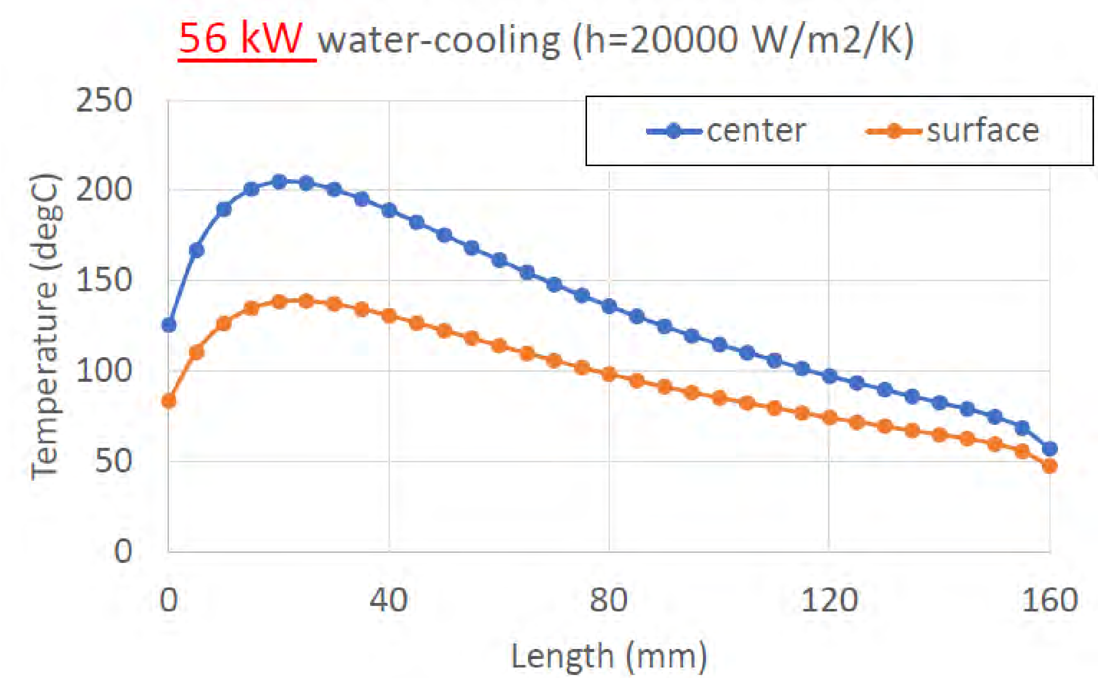
- C/C composite
- SS304, 64Ti, Inconel



Reinforcement of target support for the axial direction

Tungsten Target @ Phase-2





To yield more muons, upgrade of the target material from graphite to tungsten is needed.

Radiation cooling is not enough with tungsten target and 56kW beam power. Water cooling is needed.

Simple model shows realistic results. But further optimization is needed.

- Tungsten material itself
- Water flow
- Corrosion
- Target dimension
- Remote handling

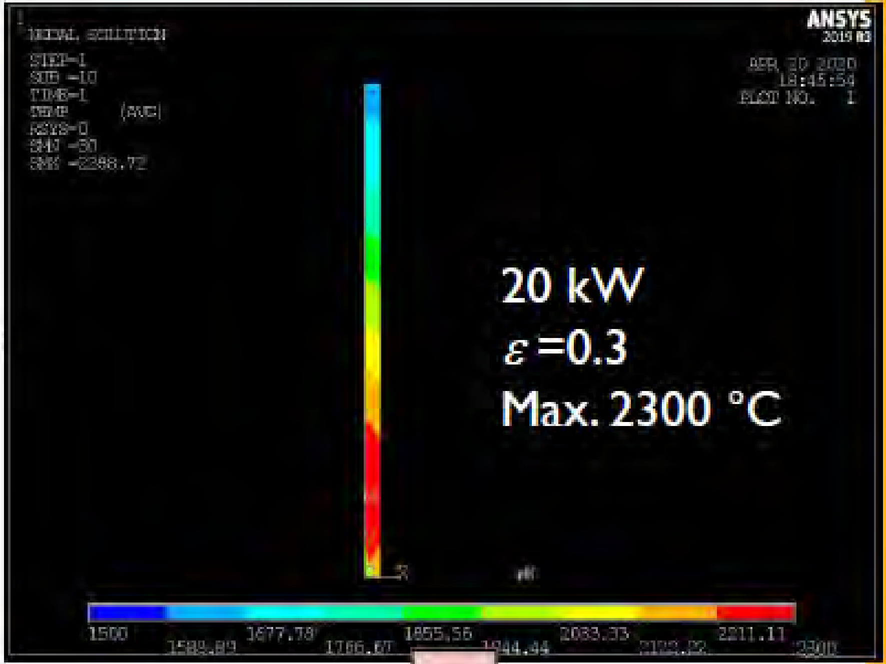
Higher performance by New TUNGSTEN and Technology

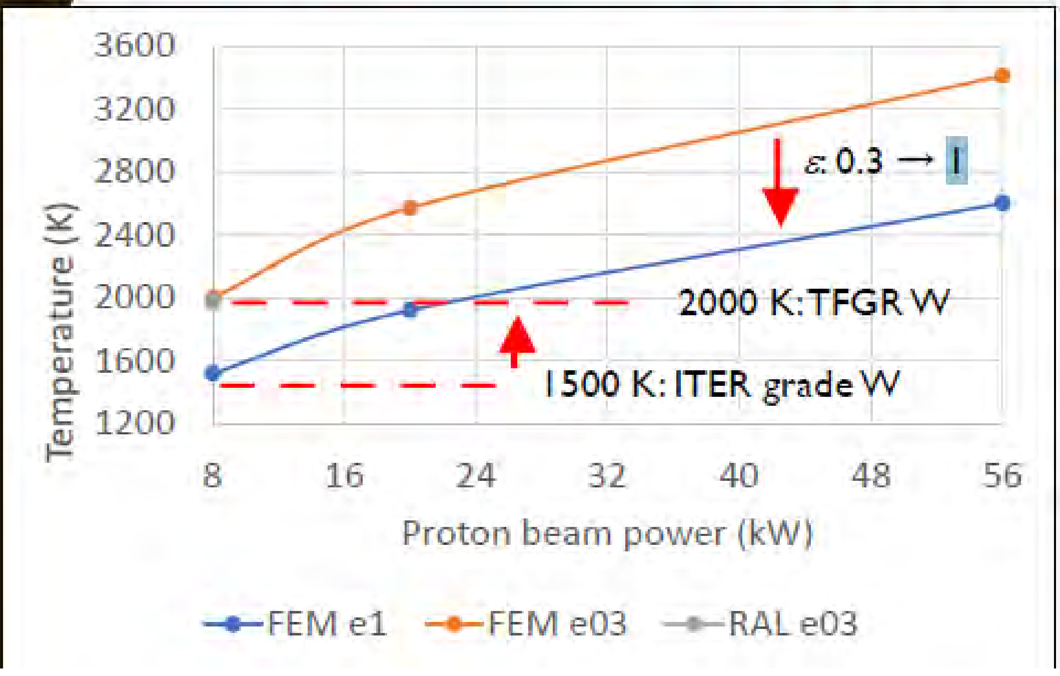
1. Developments of TFGR tungsten to improve recrystallization embrittlement
   Maximum available temperature
   ITER grade tungsten: 1200 °C
   TFGR tungsten: 1700 °C

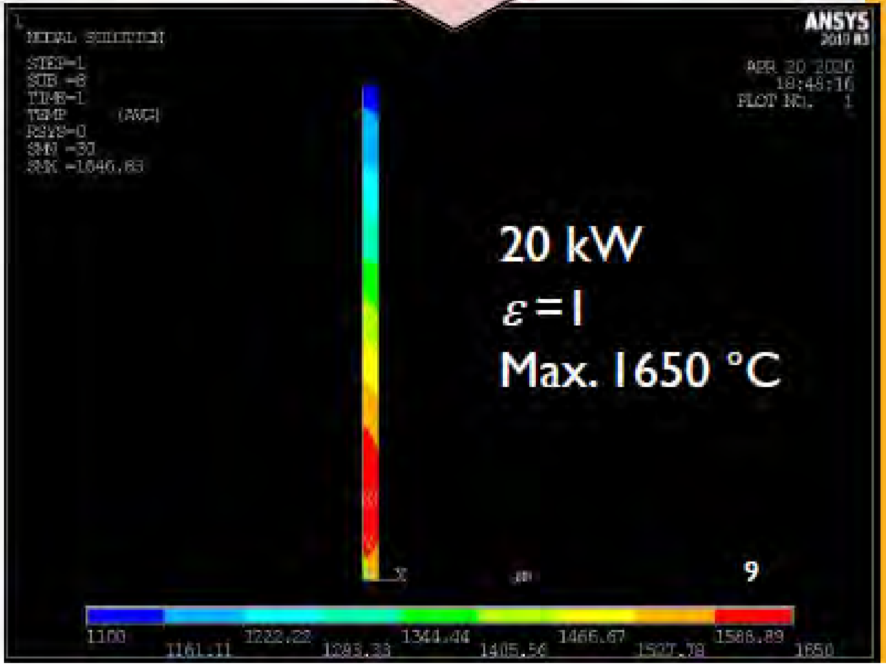
KEK-MTC collaboration, S. Makimura et al., Scientific Net, in press

2. Increment of emissivity
   Surface treatment: 0.3 ➡ 1
   Collaboration with STFC/RAL is under discussion.

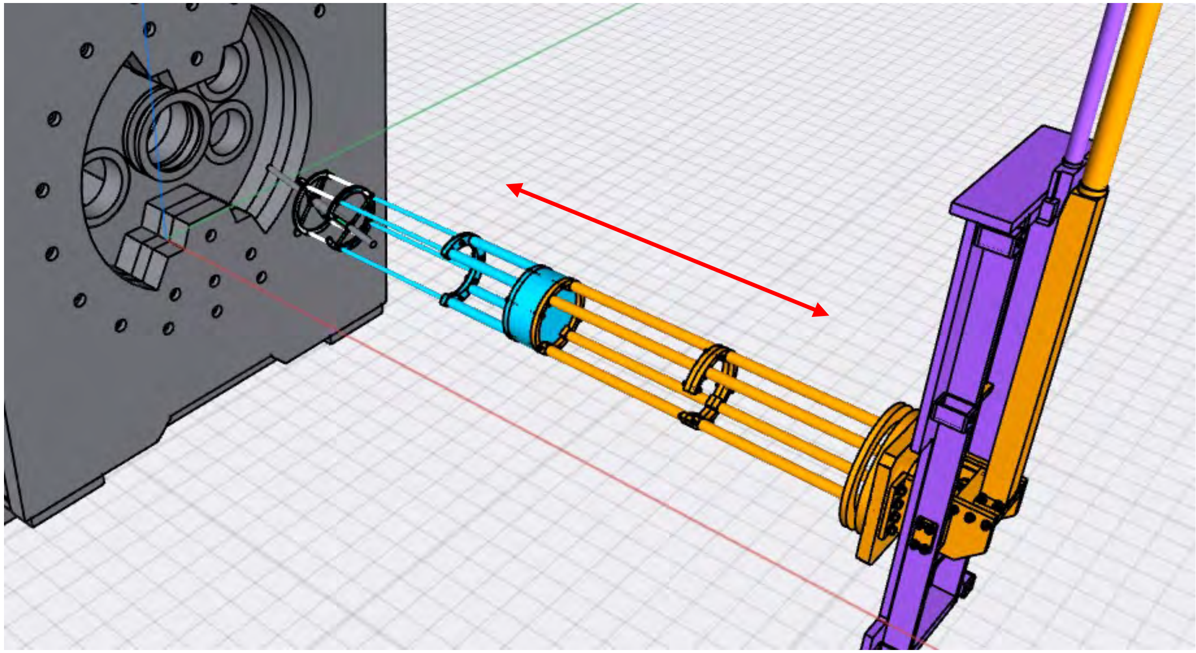
Aiming beam intensity: 20 kW



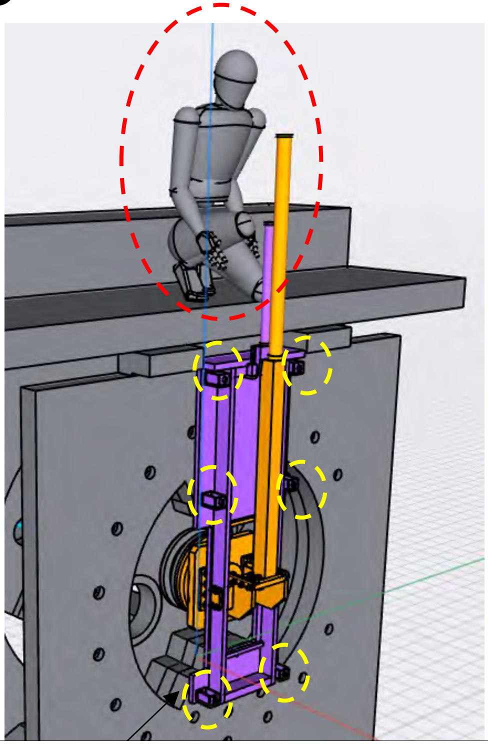




Target Assembly

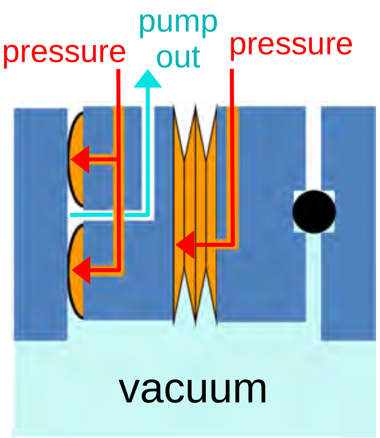


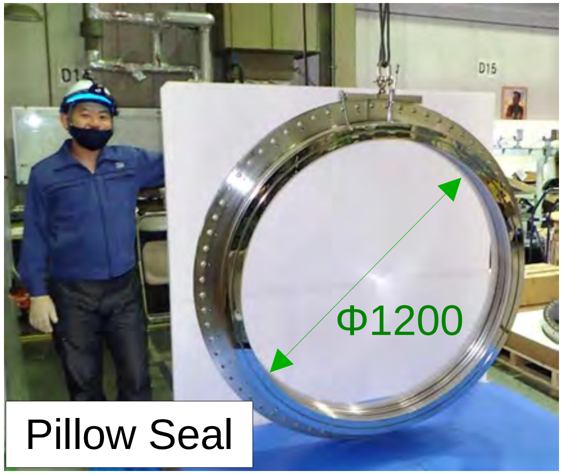
The target assembly is inserted into the solenoid shield by semi-remote-handling.



- Maintenance with local shielding
- 3000 kgf of load by the air-pressure of pillowseal must be considered.

We must consider
- How the structural strength is guaranteed.
- How the accuracy is guaranteed.
- How it is maintained in the high radiation area.





New US-JP Proposal between FNAL(Mu2e) and KEK(COMET)

Collaboration for the Muon Science. The first step is a development of the muon production target.

- COMET : Water Cooled Tungsten (56kW)
- Mu2e : Radiation Cooled Tungsten (8kW)

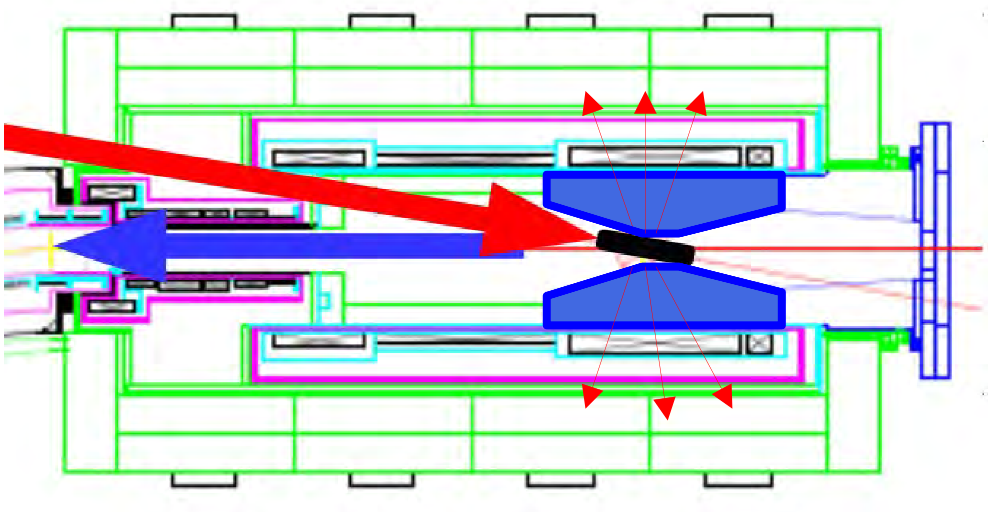
Study Items

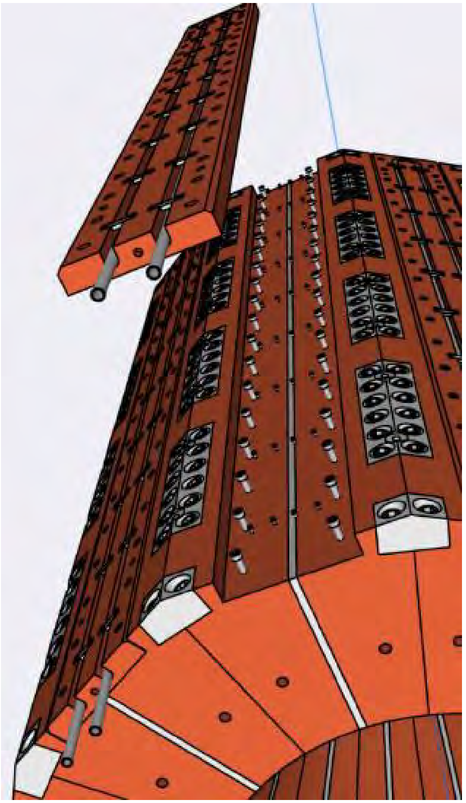
- Fatigue property
- Creep property
- Alternative W-alloy search
- Emissivity improvement
- Coating/Cladding technology against corrosion

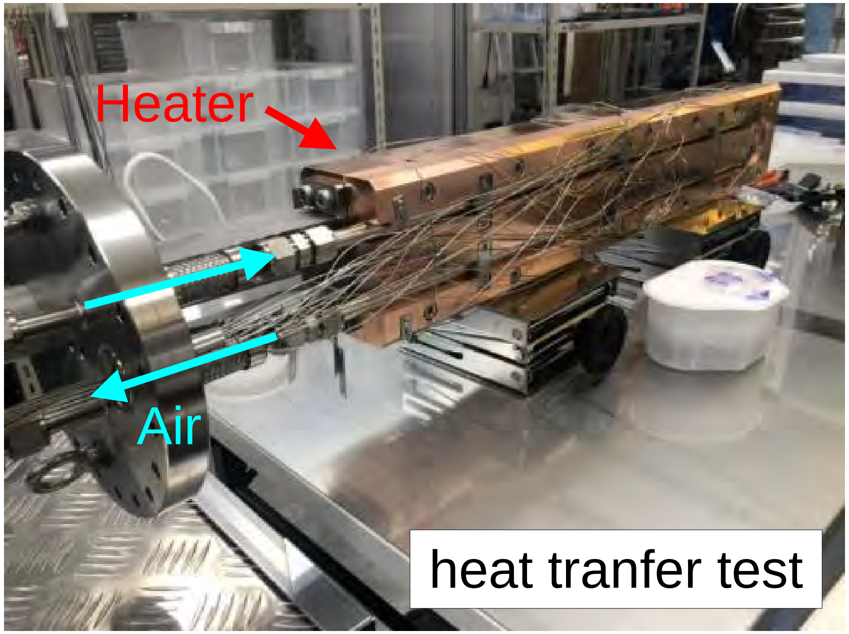
In the future, we would like to include other items.

Radiation Shield in Capture Solenoid

Massive shield is needed between the target and the superconducting coil to prevent quench.





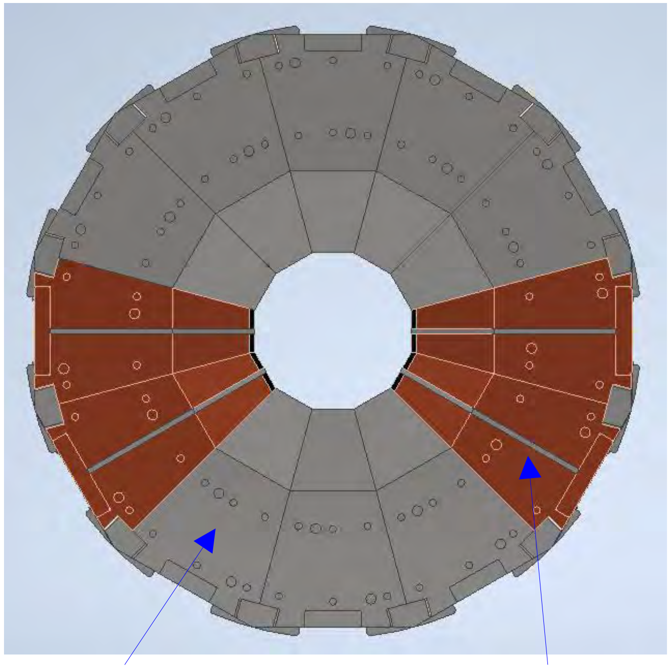


Copper / Stainless Steel will be used at Phase-I.

Further R&D is needed towards Phase-II where heavier material will be favored (tungsten, Pb).

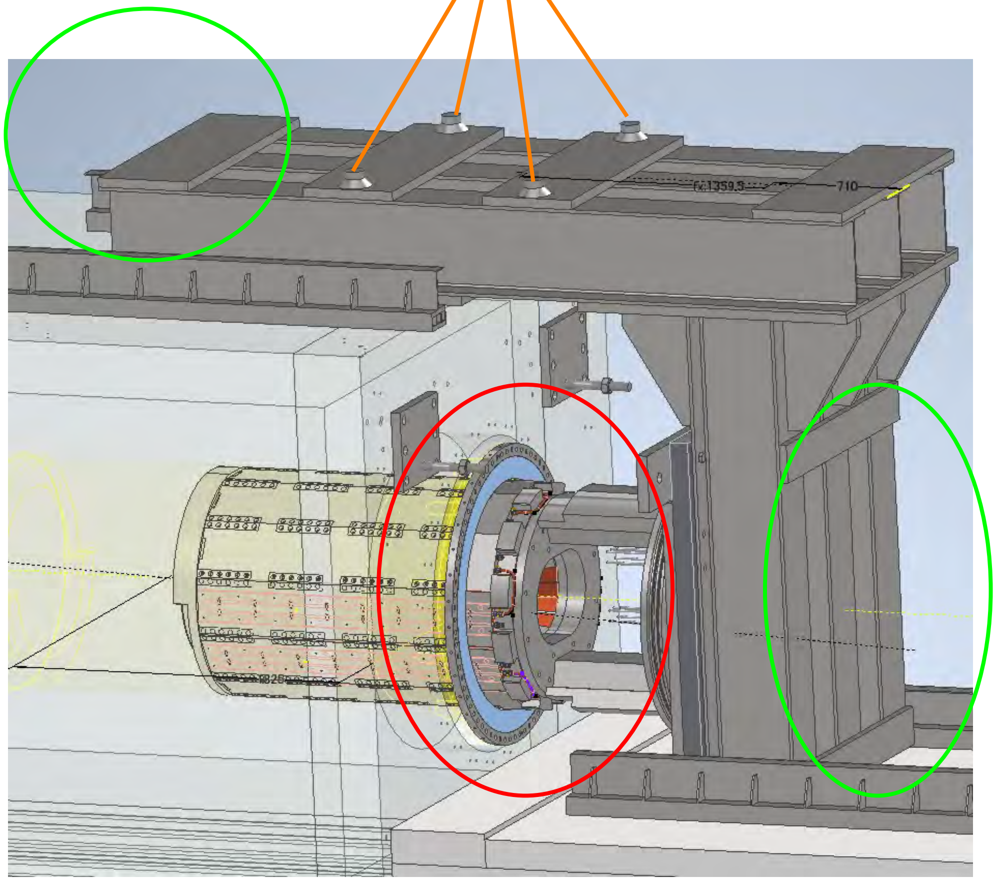
Radiation Shield in Capture Solenoid

Beam View



Stainless Steel   Copper

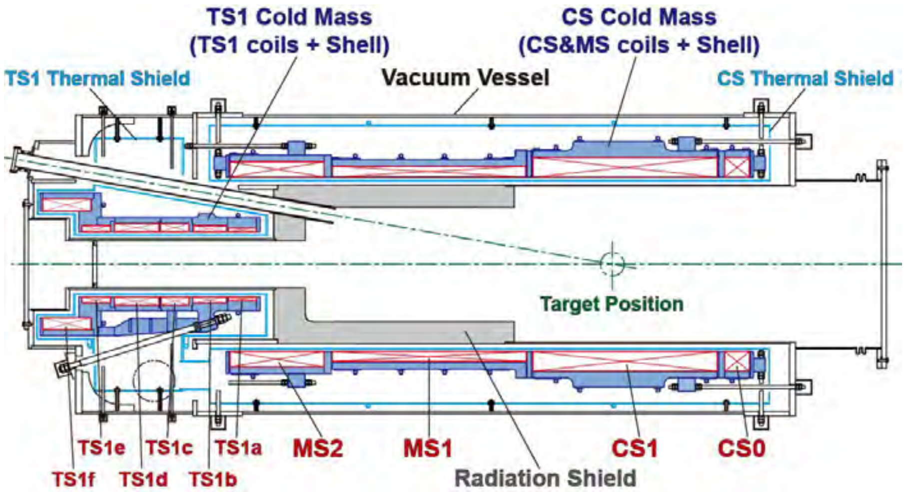
We have to replace the shield to that with the higher density material to realize Phase-2.
Design fo the scheme of the replacement is needed because high residual dose is expected.

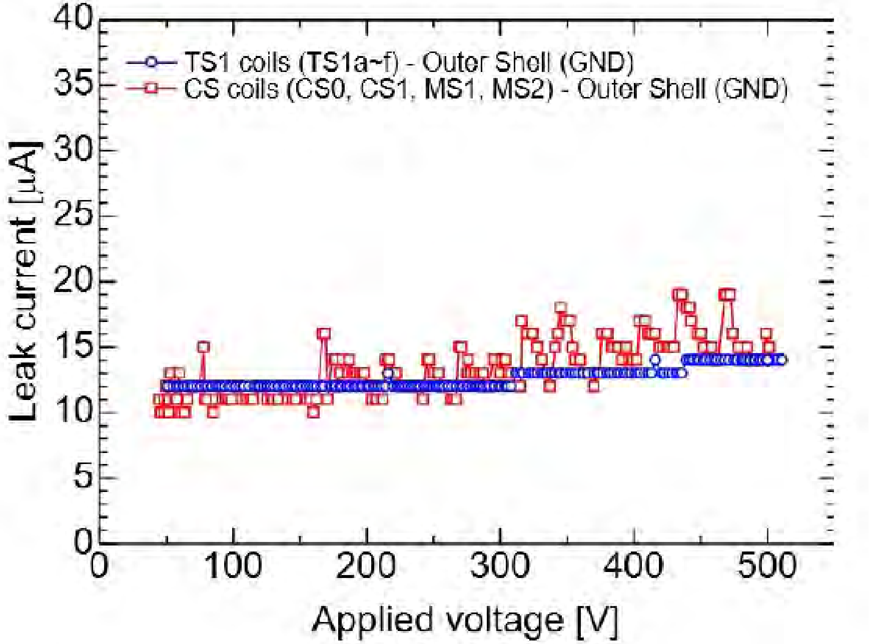


Shield material will be Stainless Steel at Phase-1.
Copper may be used at the area of high energy deposit to prevent local heat generation in the super conducting coil.

Manufacturing of Capture Solenoid

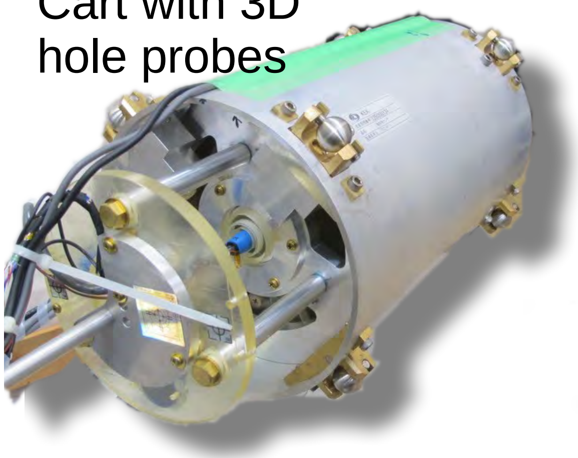
During manufacturing, grand-fault was detected. Although delay of several months occurs, repair work was completed and restarted manufacturing.



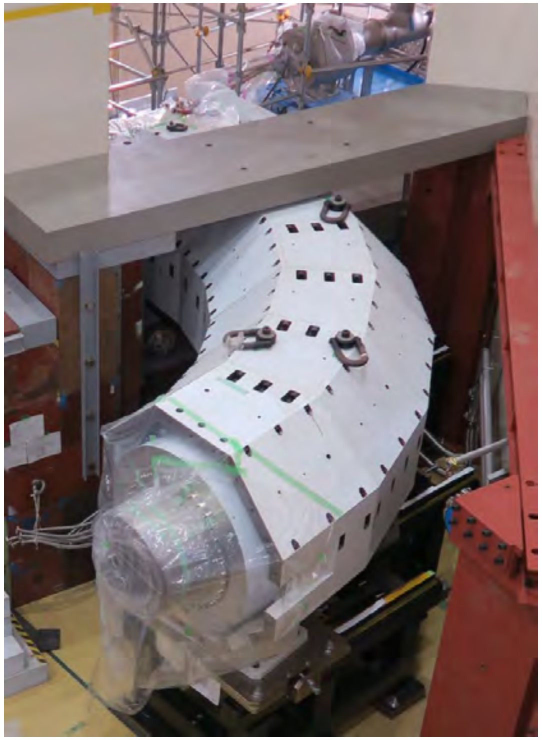


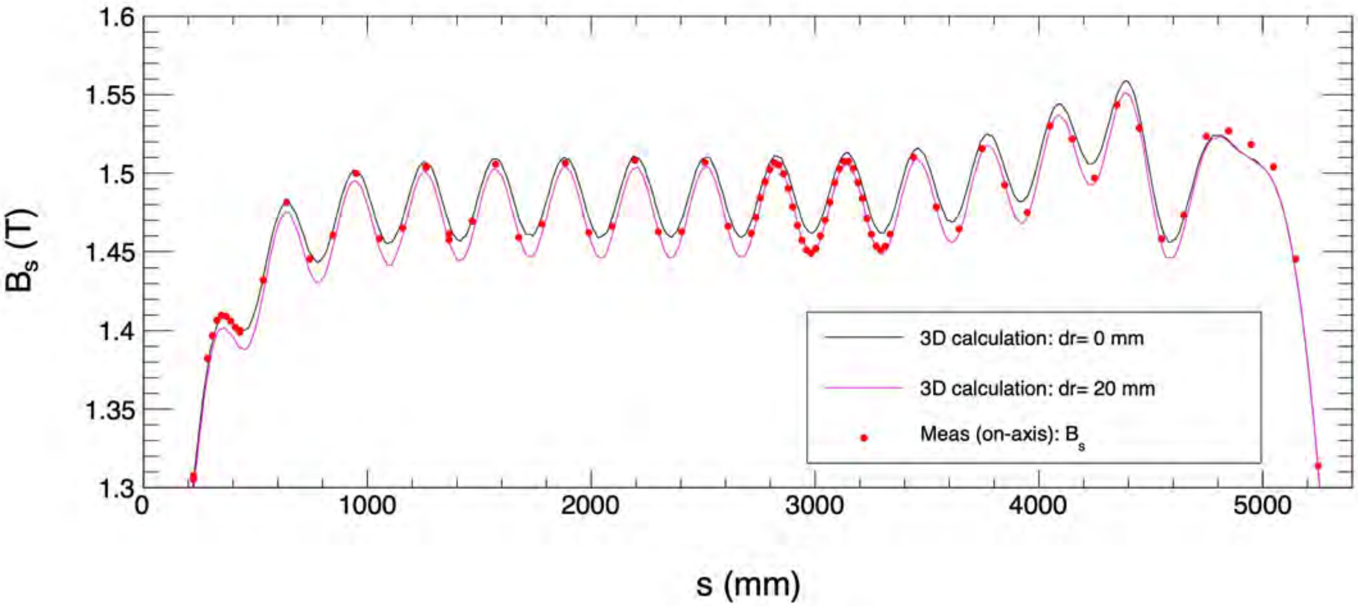
Field Measurement of Transport Solenoid

Cart with 3D hole probes



Magnetic field of the Transport Solenoid was measured by inserting the cart with 3D hole probes (and worm bore) to the beam pipe.

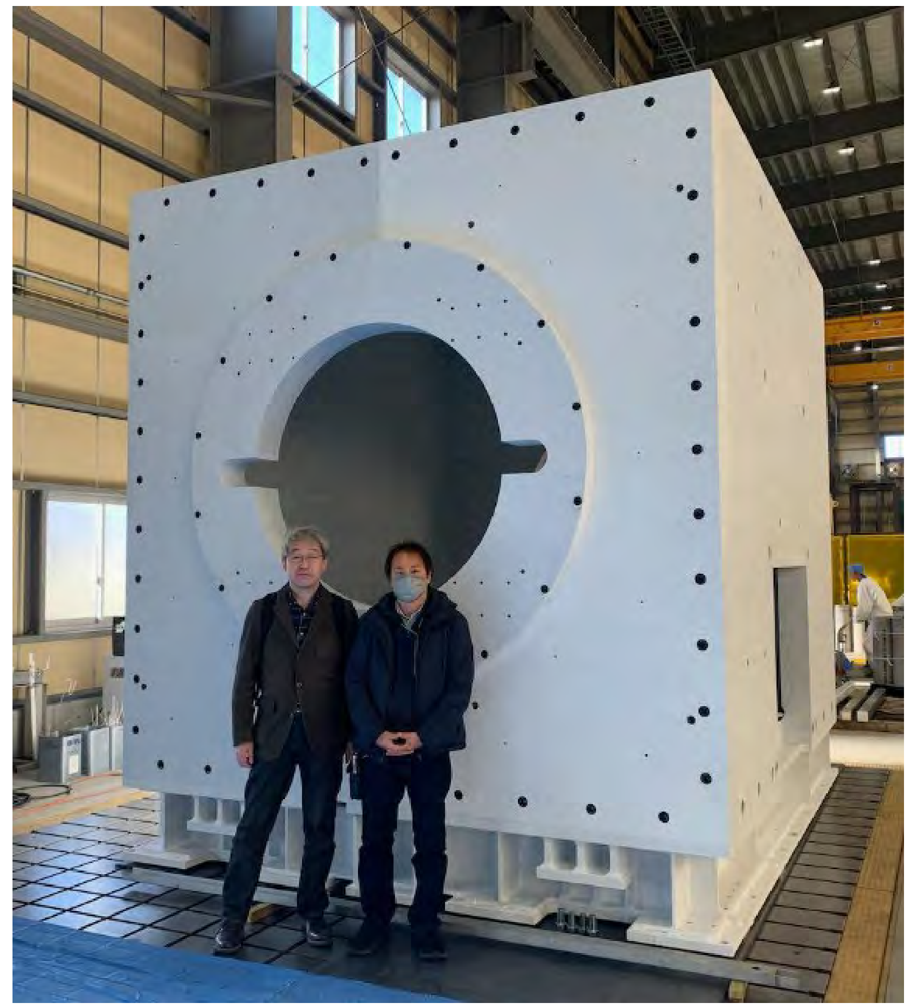




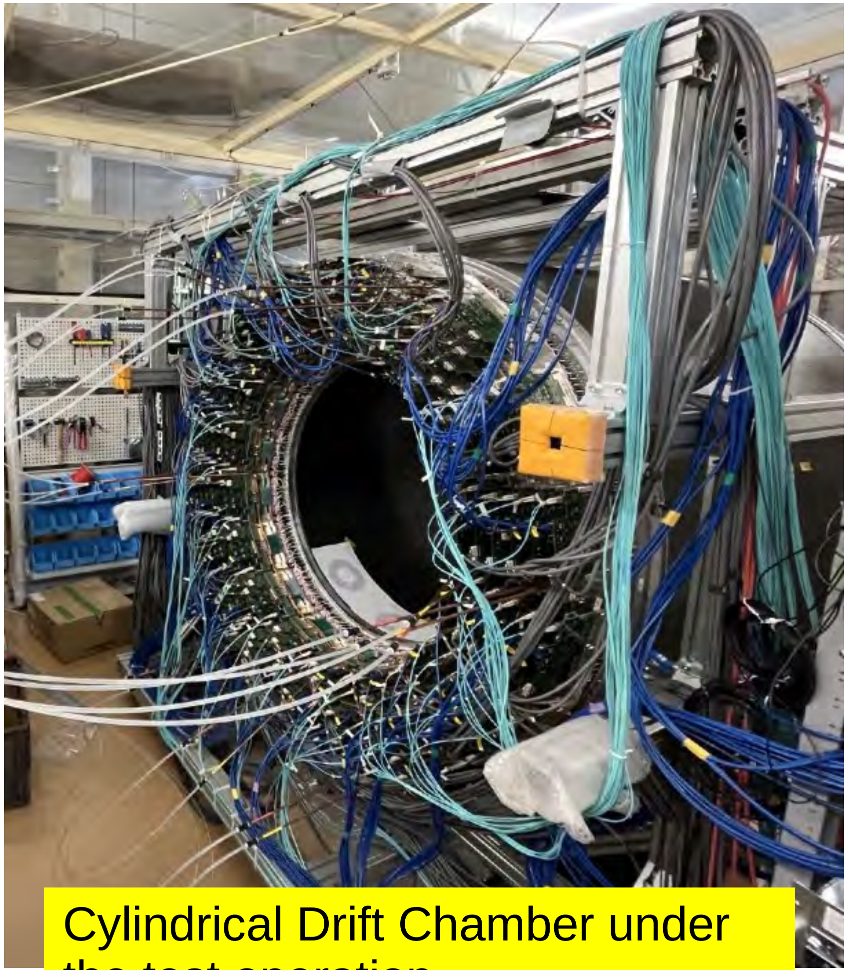
Slight discrepancy between measurements and the simulation is understood by the position shift of the cart by the magnetic field.

Detector Solenoid

Construction of the Iron yoke for the Detector Soleonid was completed. Manufacturing the Detector Solenoid is ongoing and will be completed before the next summer.



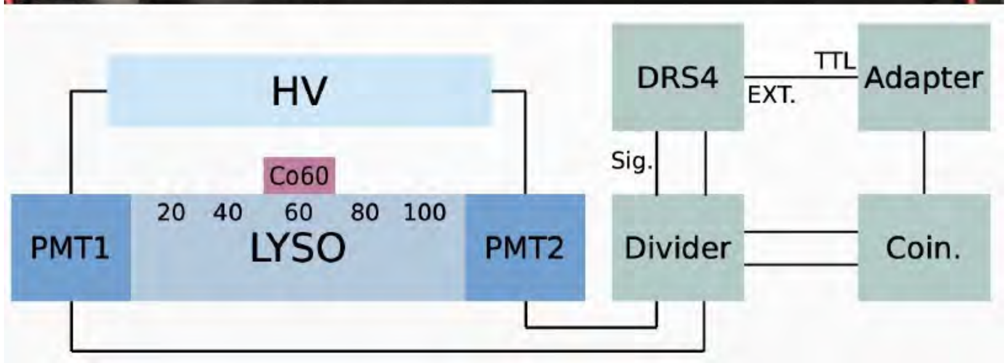
Detectors



Cylindrical Drift Chamber under the test operation

2nd Station (out of 5) of Straw Tube Tracker

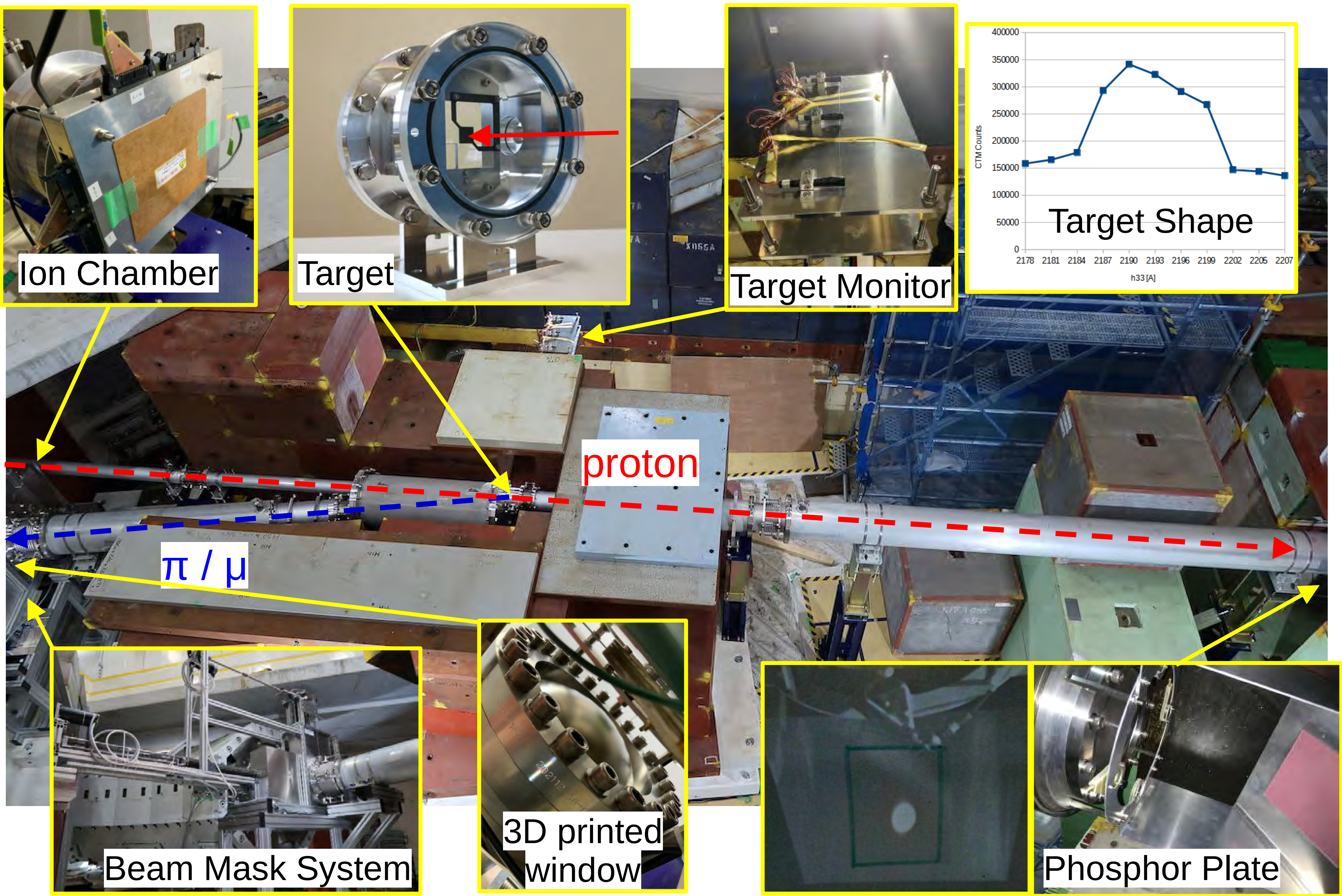
QA/QC setup for LYSO crystal



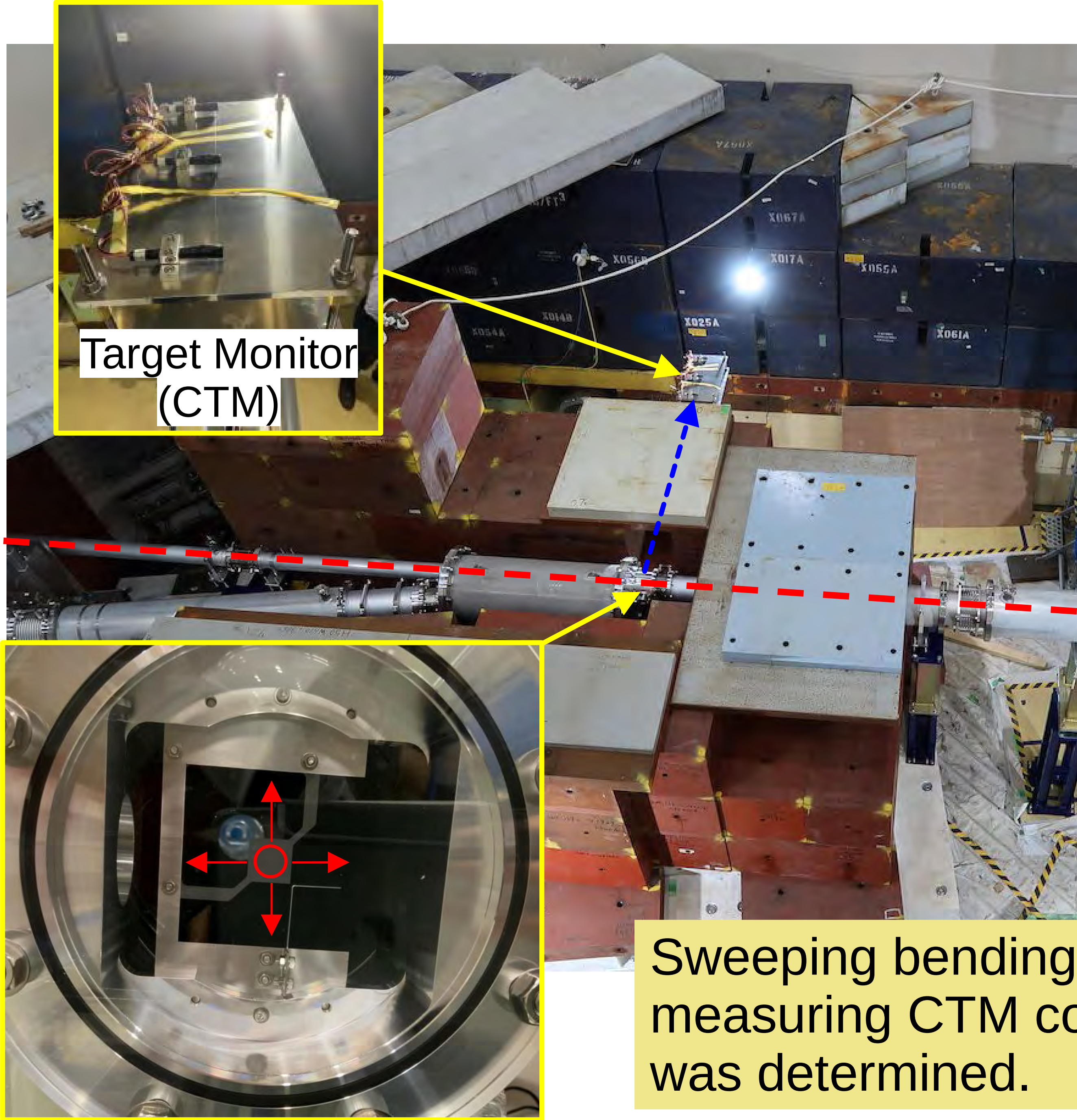
COMET Phase-alpha
(Beam Commissioning Run)

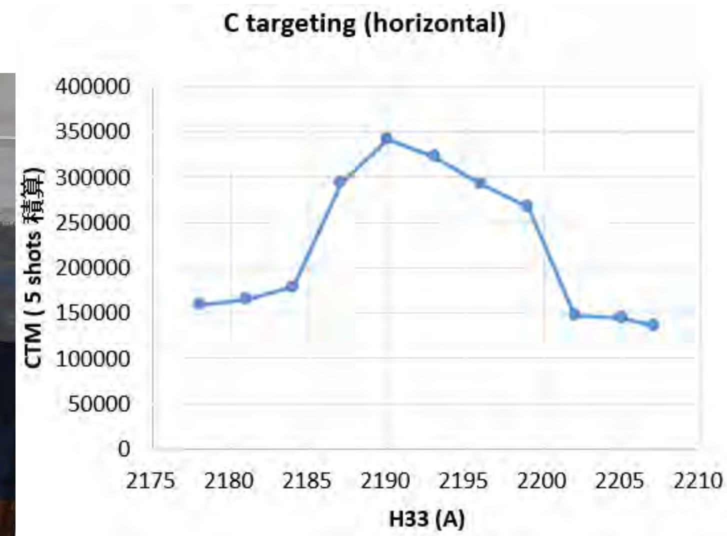
Proton Beam Commissioning

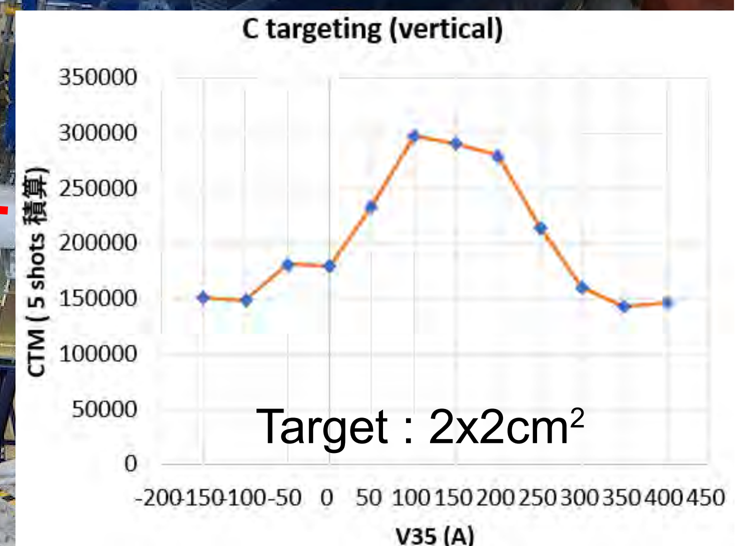
Proton Beam Commissioning



Target Scan

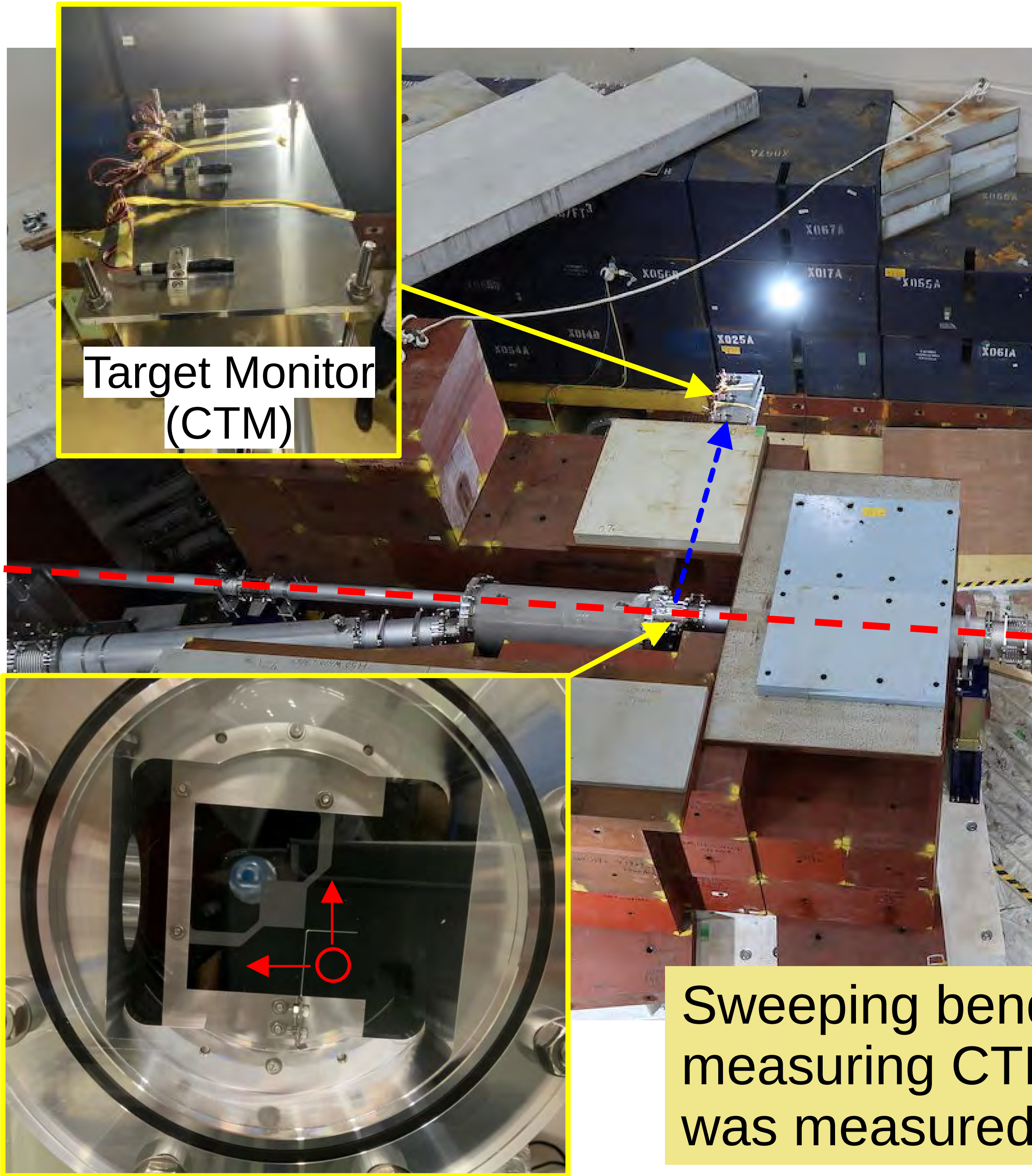


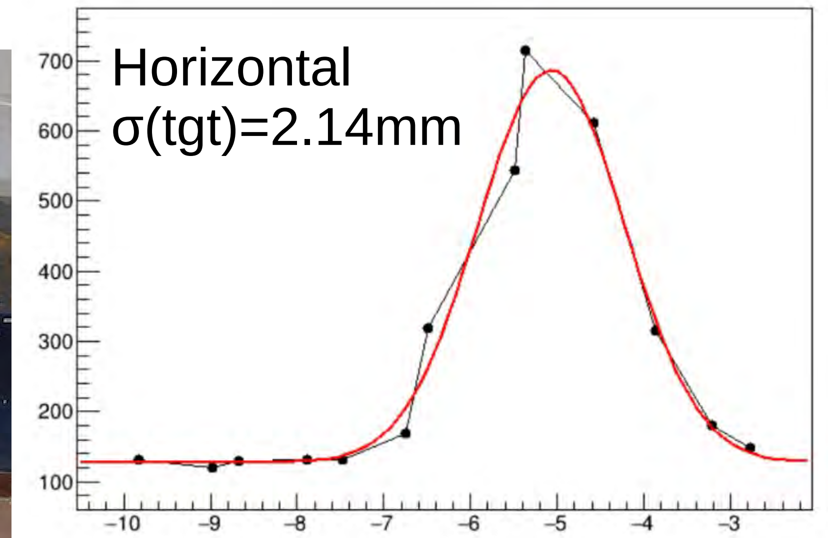


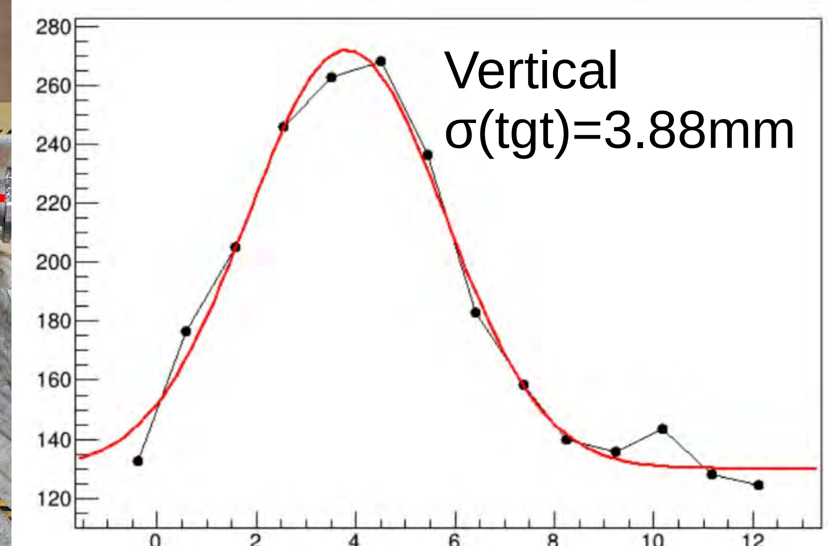


Sweeping bending magnet (H33 / V35) and measuring CTM counts, center of the target was determined.

Beam Profile at Target

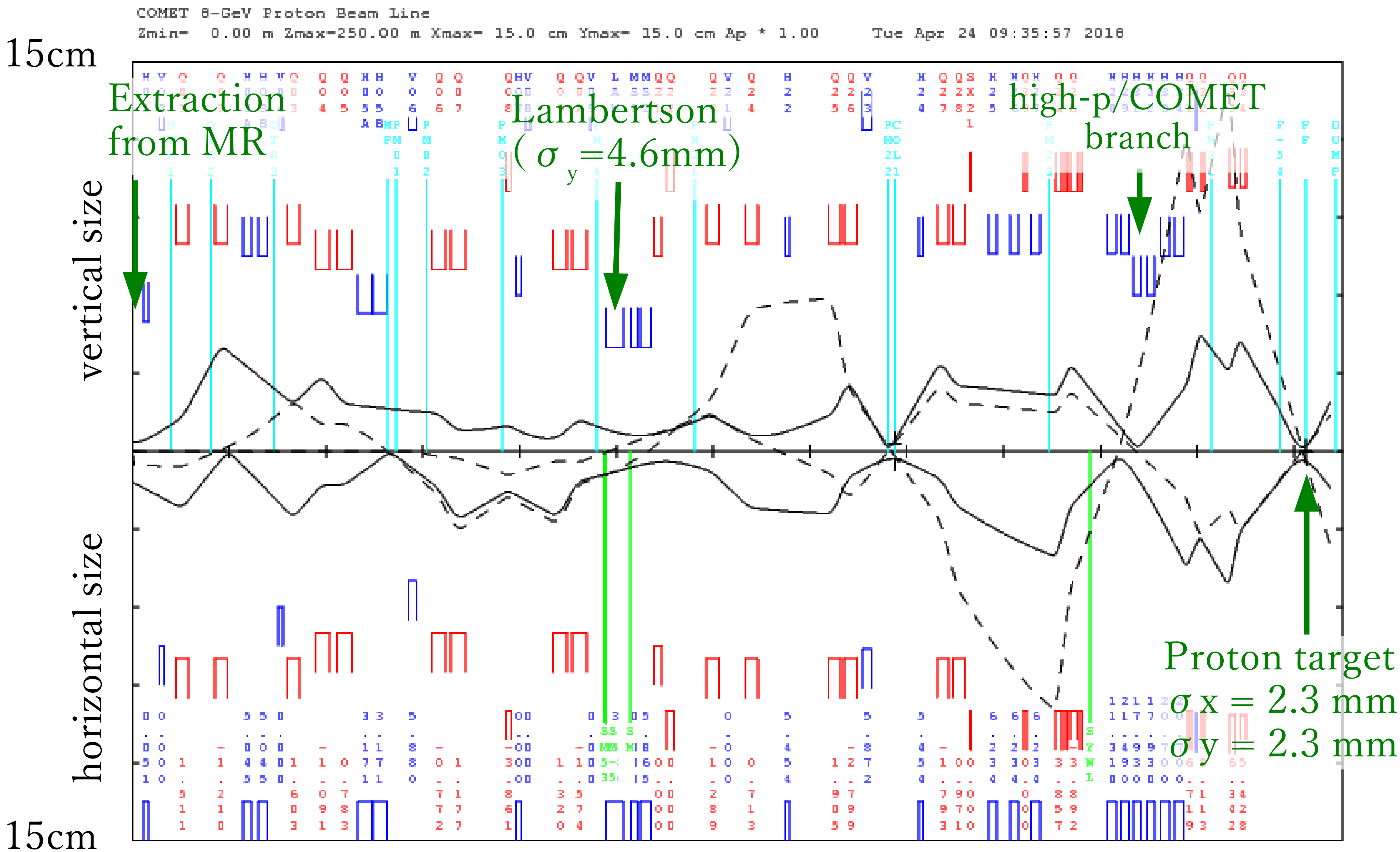






Sweeping bending magnet (H33 / V35) and measuring CTM counts, profile at the target was measured.

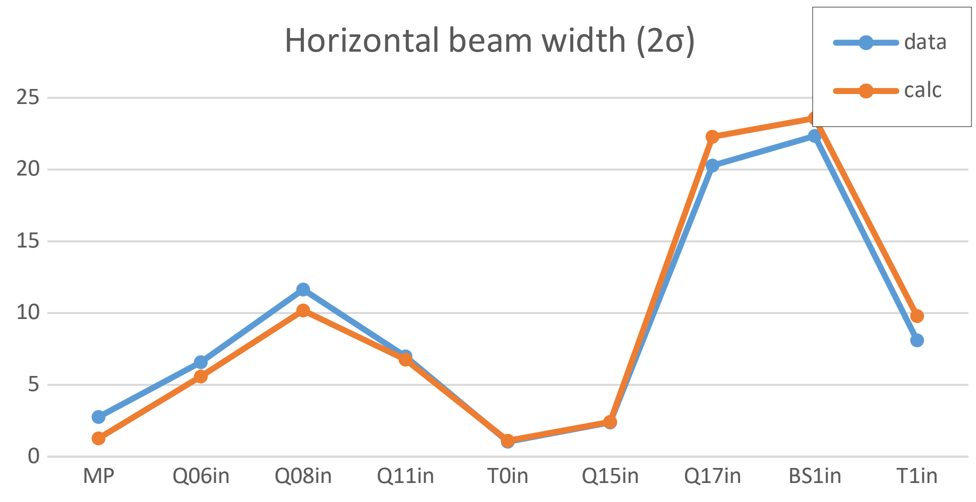
Proton Beam Optics

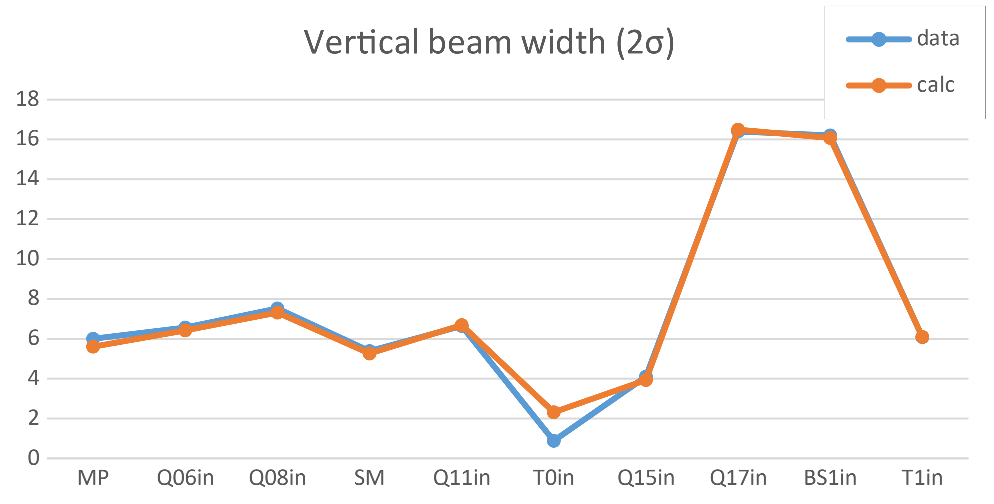


Proton Beam Optics is evaluated using PSI TRANSPORT.

Proton Beam Emittance

Emittance at phase-α was evaluated by the beam profile measurements at the A-Line.

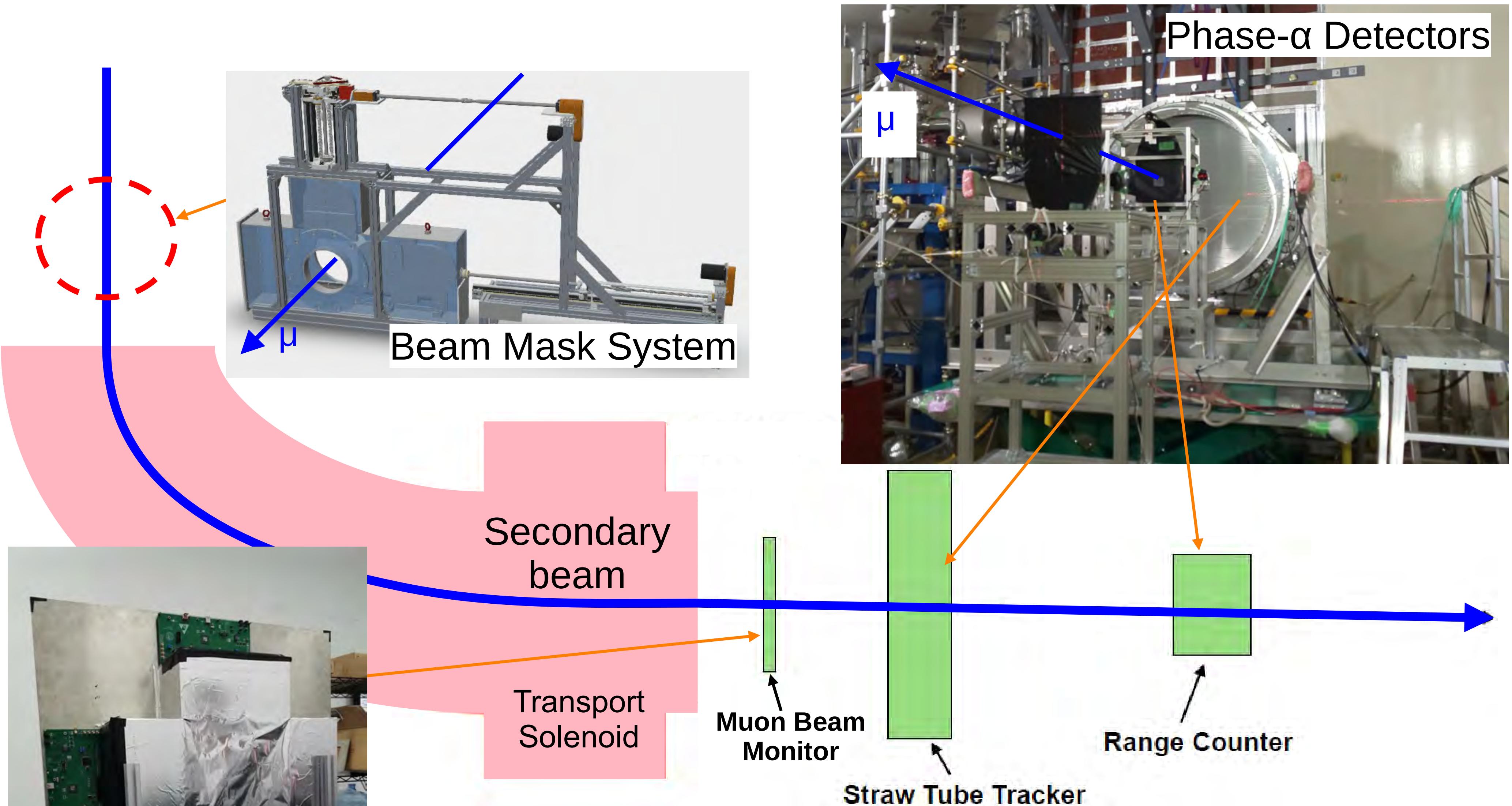




[yymmdd]	$\varepsilon_H(2\sigma)$ [mm mrad]	$\varepsilon_V(2\sigma)$ [mm mrad]
230209	***0.26***	***1.15***
210521	0.04	2.26

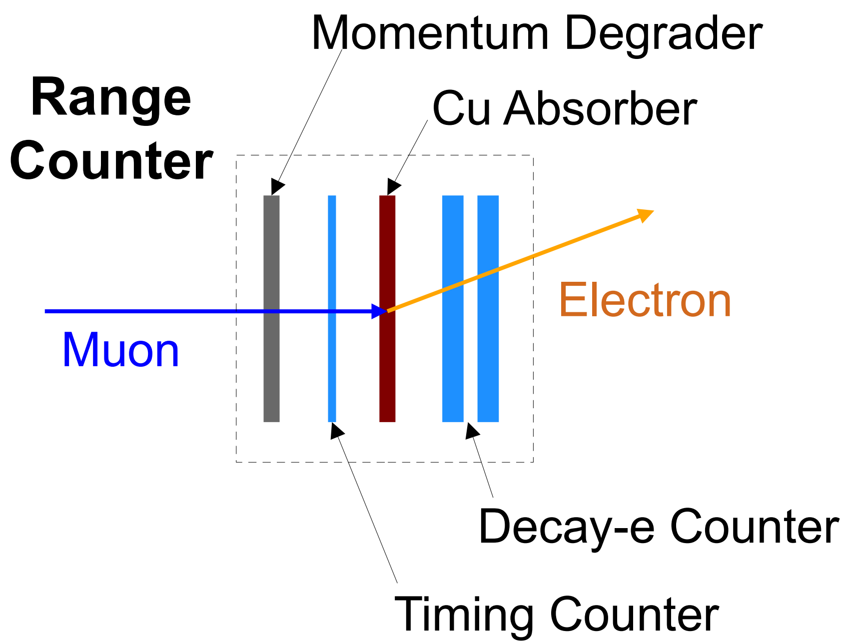
[yymmdd]	σ_X [mm]	σ_Y [mm]
Measurement	***2.1***	***3.9***
Calculation (Phase-I)	2.3	2.4

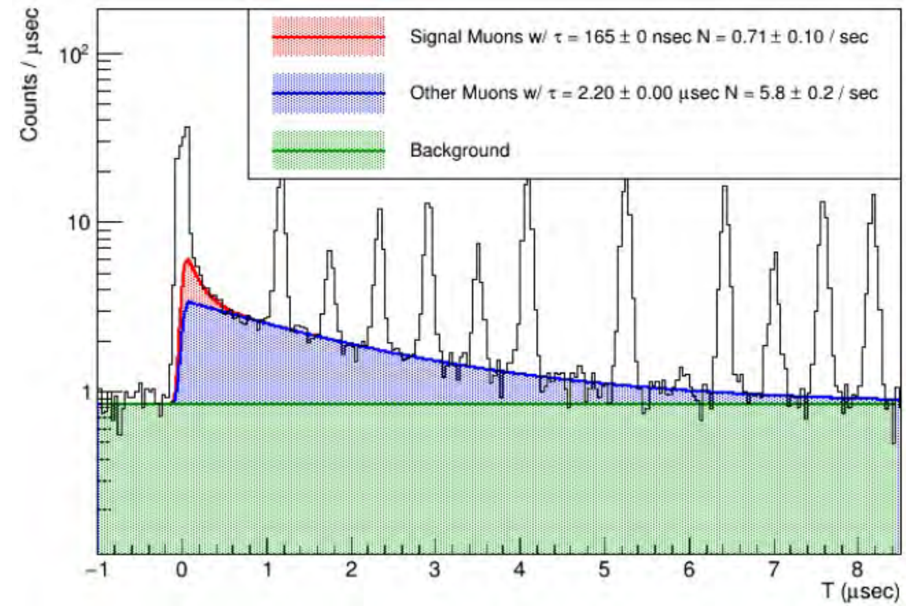
Muon Beam Measurements



Beam operation was performed for ~14 days from 2/10 to 3/15.
- Muon beam profile / yield, background particles
- Transfer matrix of the Transport Solenoid

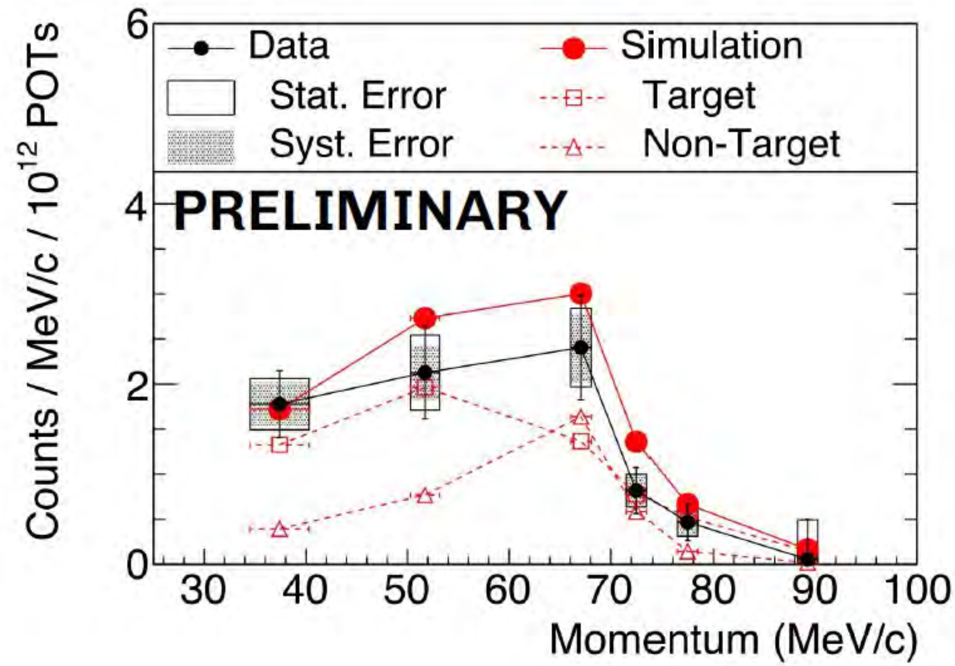
Preliminary Muon Data





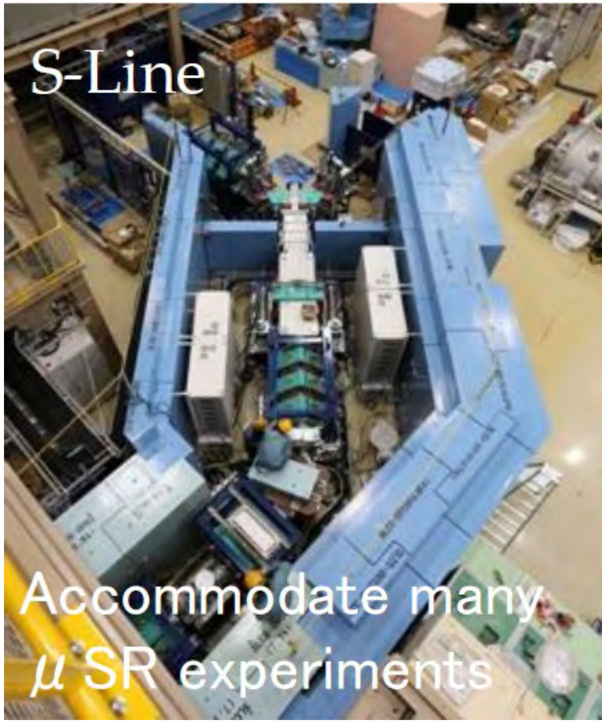
By measuring decay time distribution of muons using Range Counter, we evaluated muon yield. Short component of the decay time of ~165ns in Cu was observed.

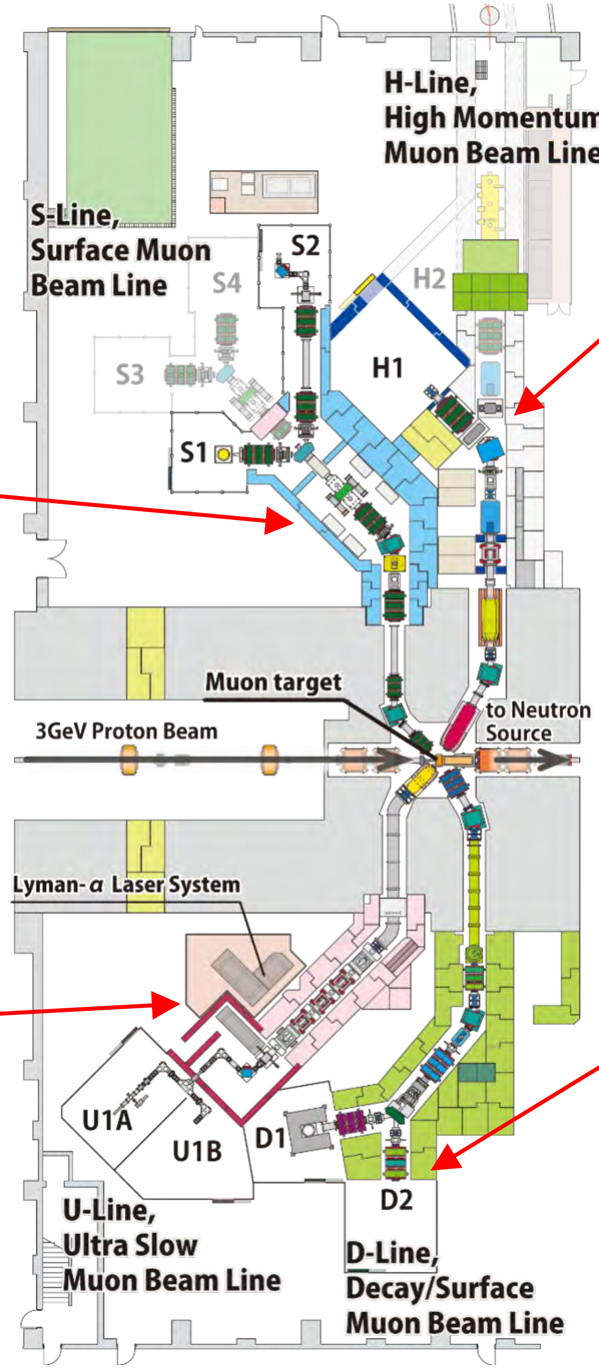
By changing degrader, momentum distribution can be extracted.

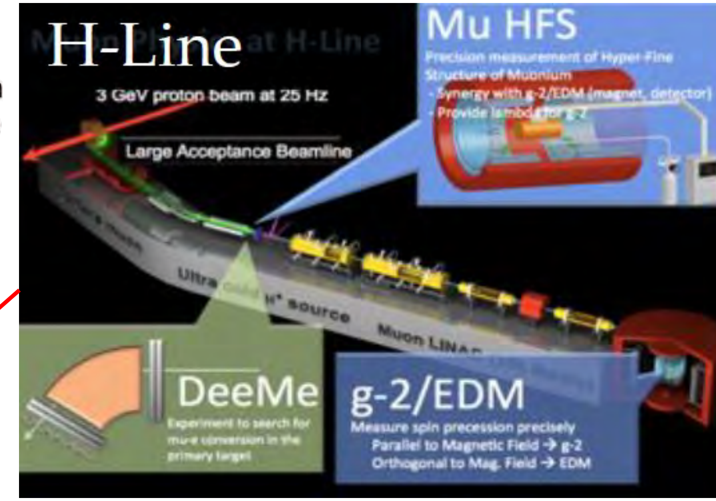


Particle Physics using Muons at J-PARC MLF

Muon Beamline at MLF



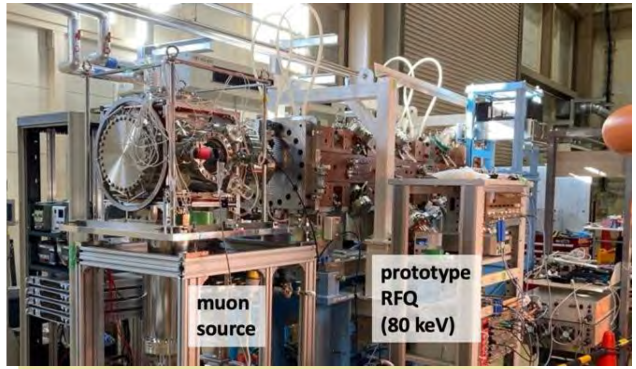




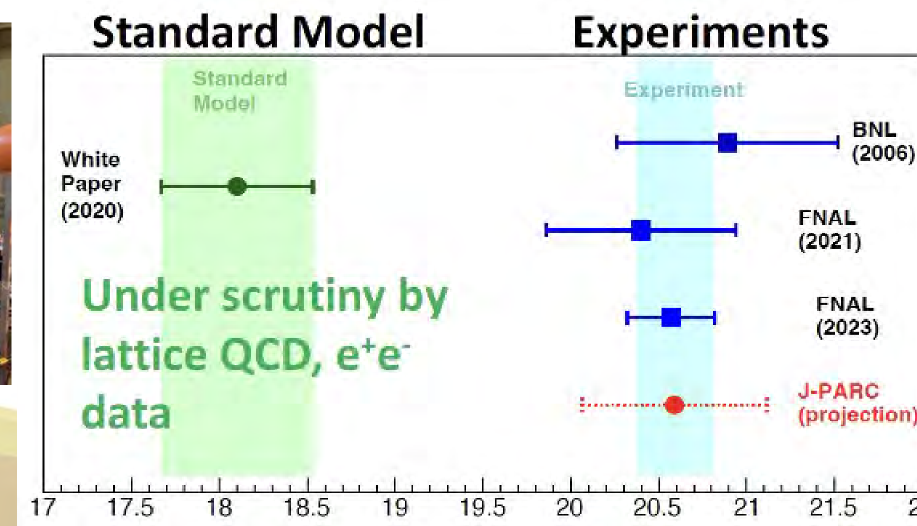
K. Shimomura (BRIDGE2023)

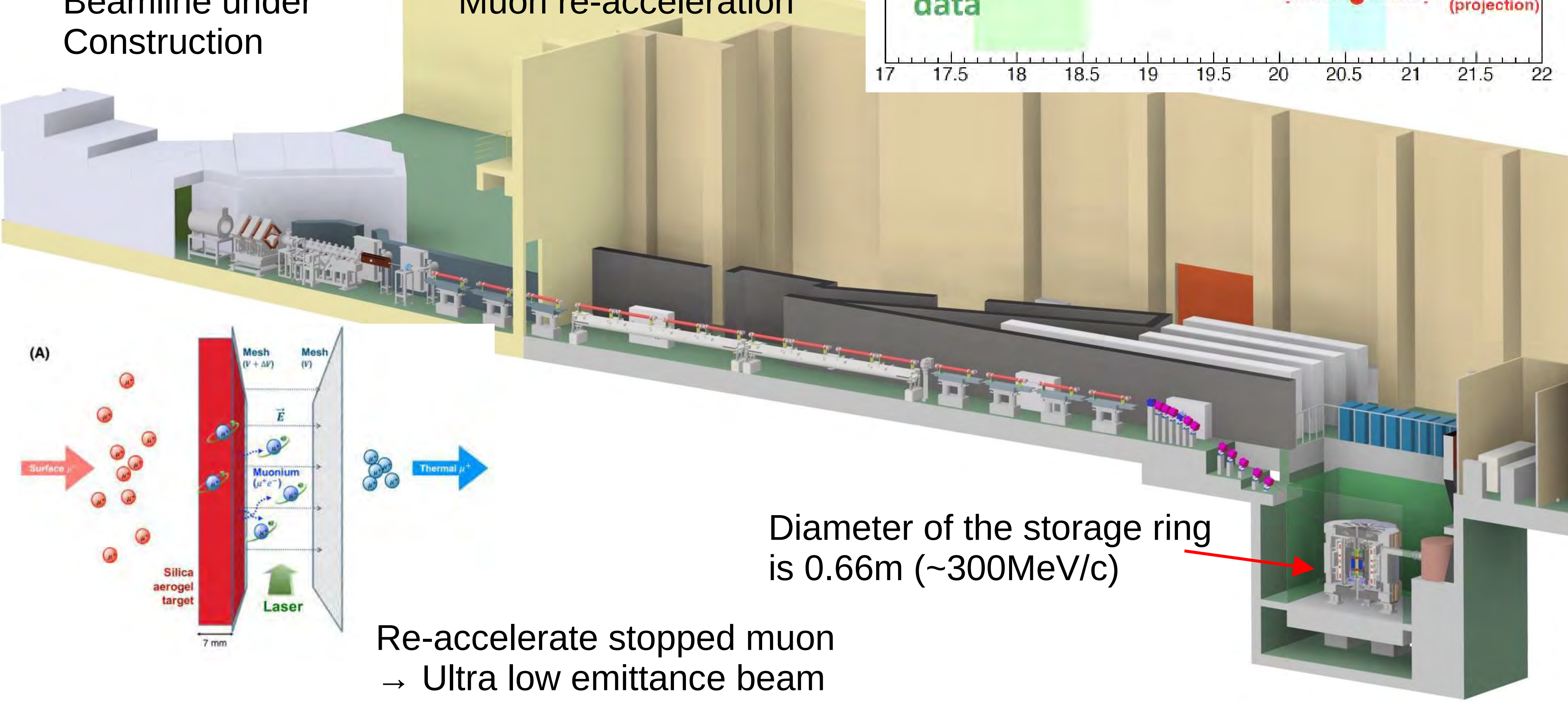
Muon g-2/EDM

Beamline under Construction



Muon re-acceleration

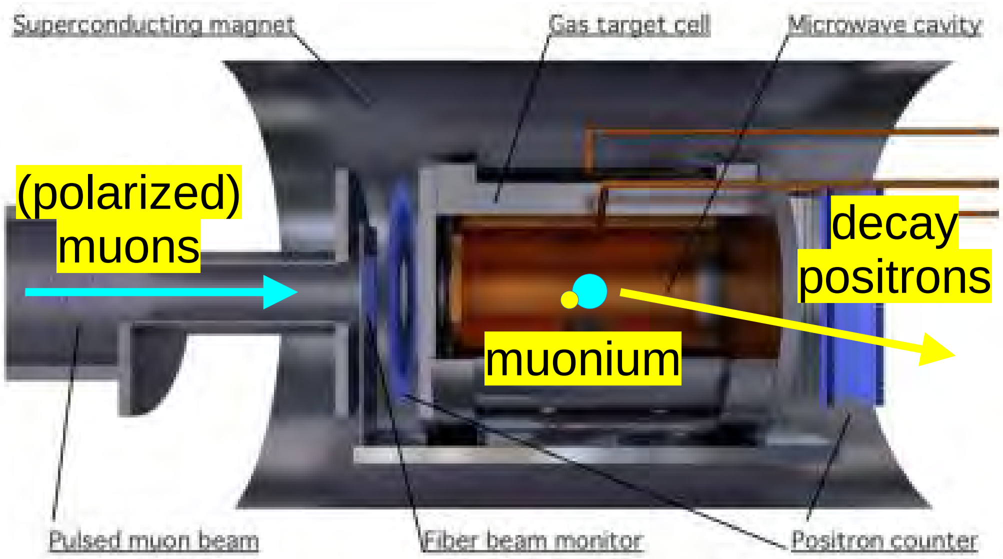




Diameter of the storage ring is 0.66m (~300MeV/c)

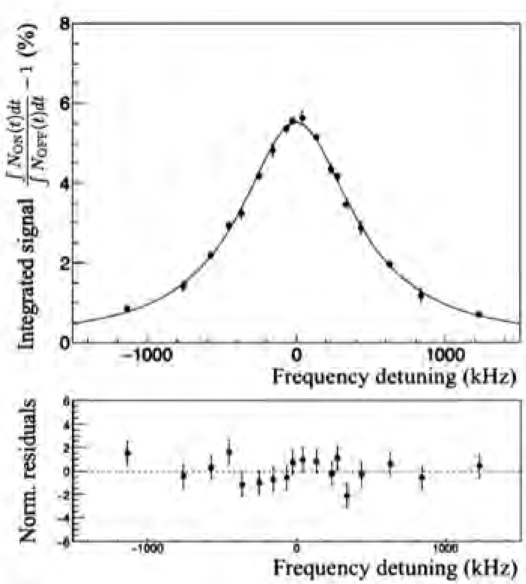
Re-accelerate stopped muon
→ Ultra low emittance beam

MuSEUM (Muonium Hyperfine Splitting Measurements)

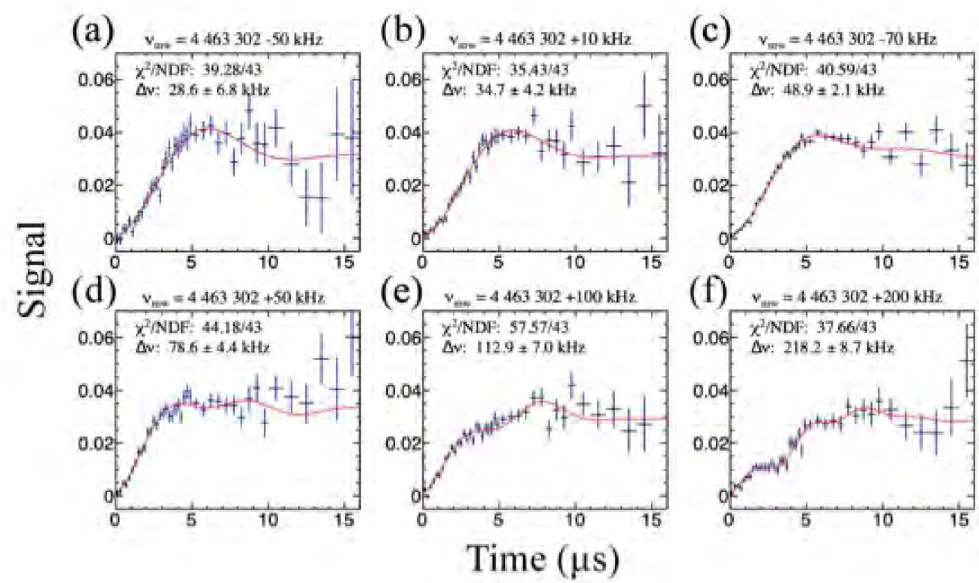


By applying RF, which is equivalent to the muonium HFS, muon spin is flipped.

Time dependence of the signal amplitude depends also on HFS. The global fitting results in more precise value of HFS.



Resonance frequency corresponds to the muonium HFS.



Summary

The Construction of the COMET experiment is ongoing in J-PARC. The first beam operation was carried out for the beamline commissioning (Phase-alpha). The proton beam was successfully delivered to the COMET Facility and secondary muons were detected after Transport Solenoid.

Manufacturing of the remaining components are underway towards the next beam operation for physics measurements in 2026.