大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

J-PARC MLF

MSL
Muon Science Laboratory
Institute of Materials Structure Science
High Energy Accelerator Research Organization,KEK

J-PARC muon facility

Takayuki YAMAZAKI

Muon4Futue, Venezia
29 May 2023

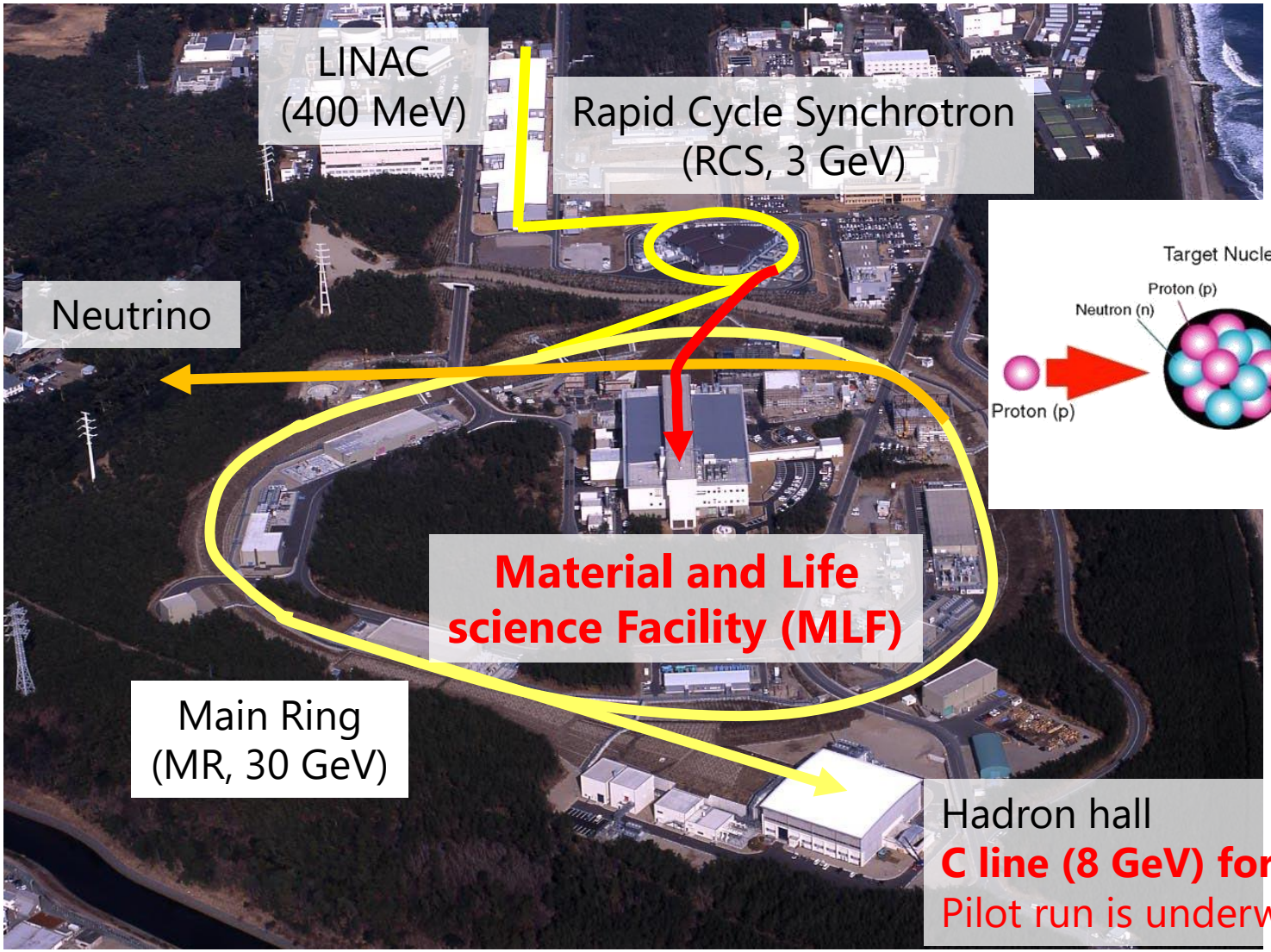
Contents

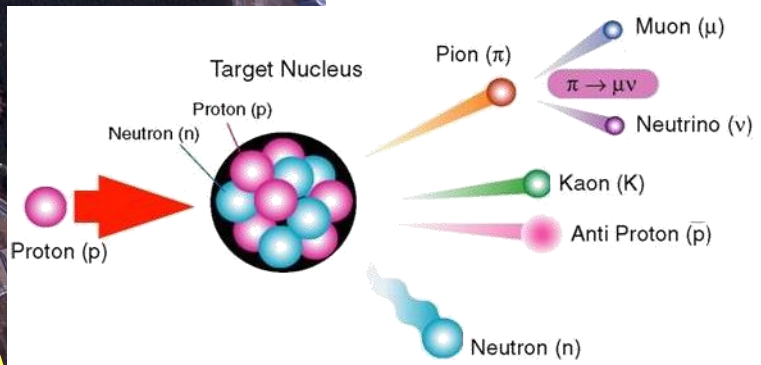
- J-PARC muon facility
- New beamlines for fundamental physics
  - S2 area: Muonium 1S-2S (precise measurement of m_μ)
  - H line: Muonium HFS (MuSEUM), $\mu^- N \rightarrow e^- N$ (DeeMe)
- Future extension of H-line
  - Low emittance muon beam for muon g-2/EDM and transmission muon microscope
- Future program: 2nd target station

J-PARC muon facility

J-PARC

J-PARC (Japan Proton Accelerator Research Complex)

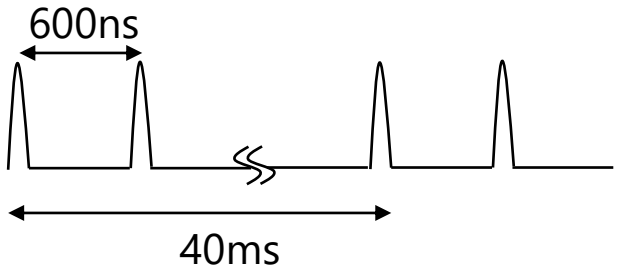


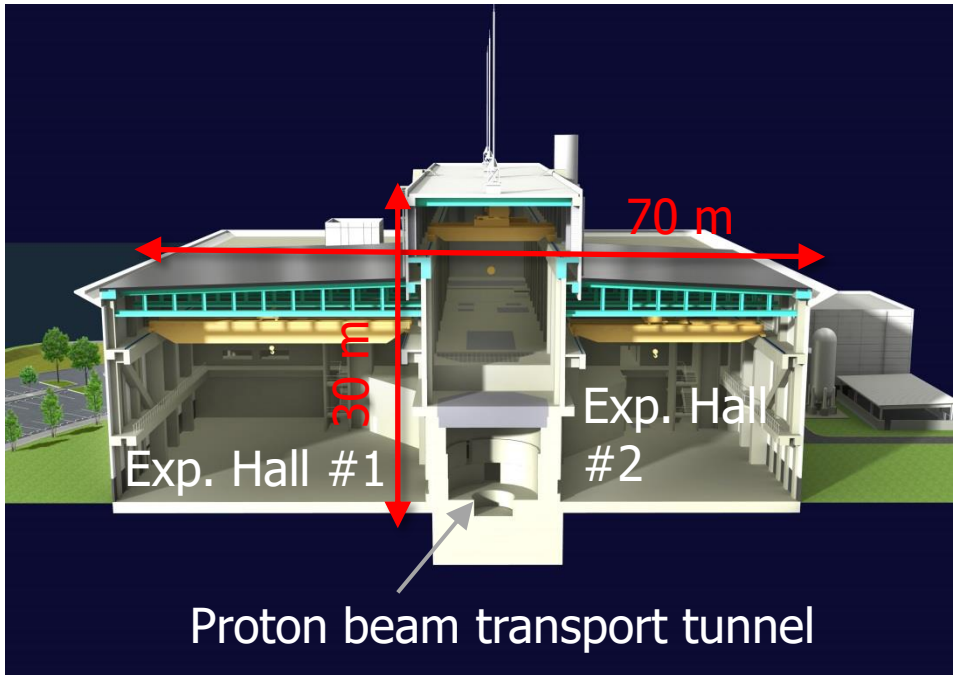


MLF

MLF (Material and Life science Facility)

- Beam power 1 MW (~840 kW stable operation at present)
- Repetition rate 25 Hz, double bunches
- Tandem target: 5% for μ, 95% for n





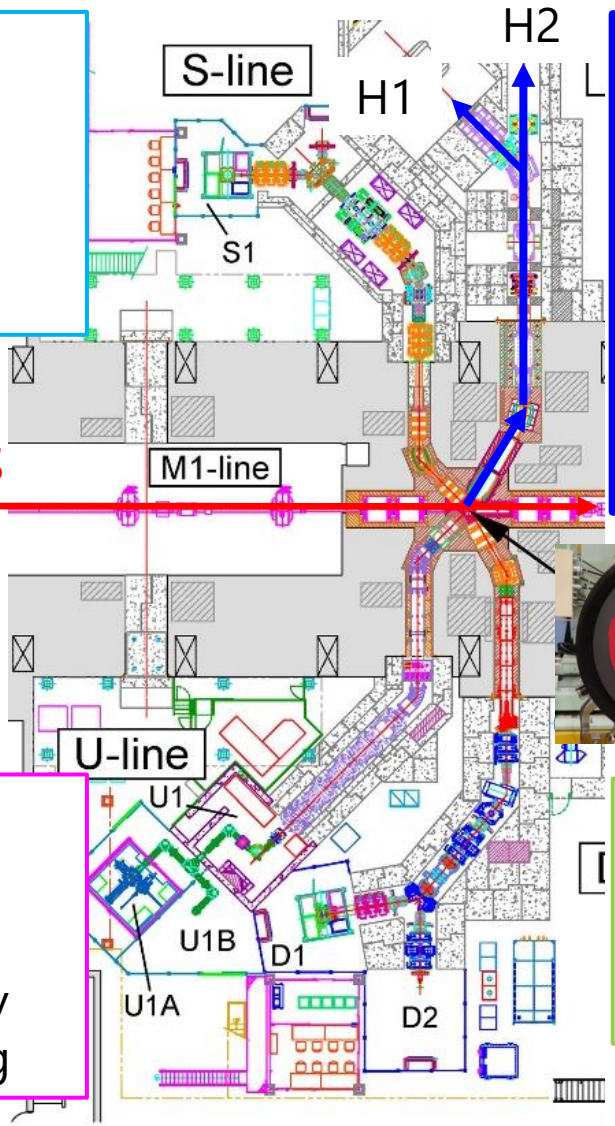
Experimental hall #1

J-PARC muon facility

- MUSE (MUon Science Establishment) in MLF

S line
- surface μ^+
- S1 for μSR
- **S2 for Mu 1S-2S**
- S3/S4 are planned

H line
- surface μ^+ (10^8 μ^+/s), cloud μ^+/μ^- (up to 120MeV/c)
- for high intensity & long beamtime experiments
- **H1 for Mu HFS & $\mu^-N \rightarrow e^-N$**
- **H2 for g-2/EDM & TμM, under construction**



3GeV proton from RCS

2e15 /s @1MW

Muon target
(graphite, ^{t}20mm)
Rotating target

U line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

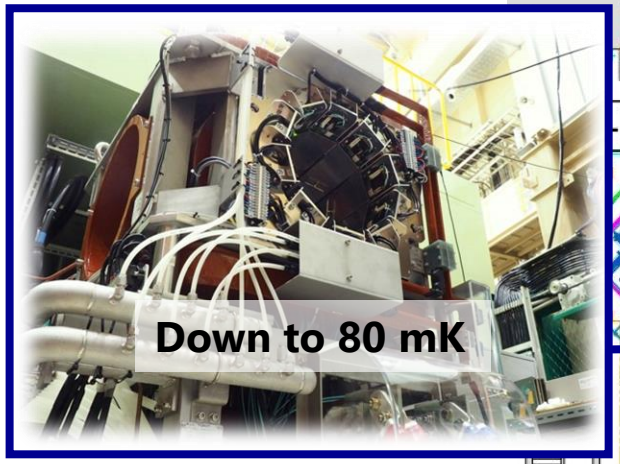
D line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for various sciences

Beamlines for material science

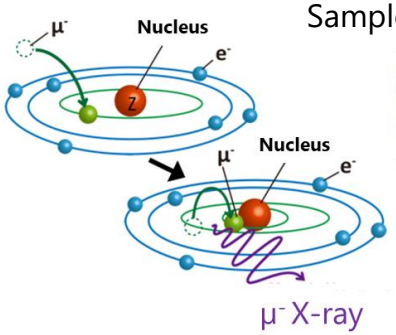
μSR Spectrometers at D1 and S1 areas

S1 Instrument: ARTEMIS (μSR)

D1 Instrument: μSR



D2 Instrument: elemental analysis using μ⁻ X-ray



Sample from asteroid Ryugu

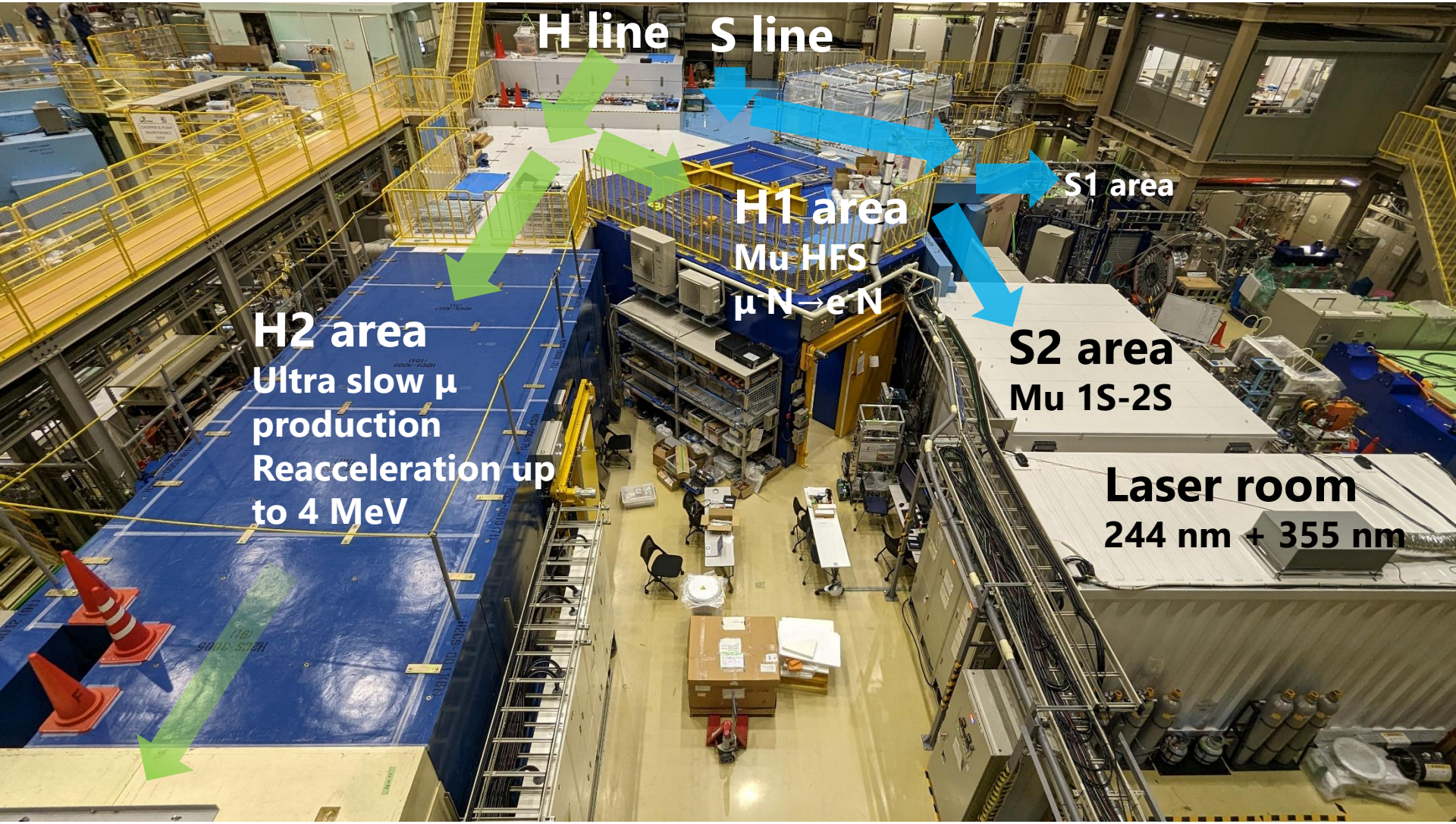
Cultural heritage

D2 area is also available for user-made one-time setup.

New beamlines for fundamental physics

H line and S2 area

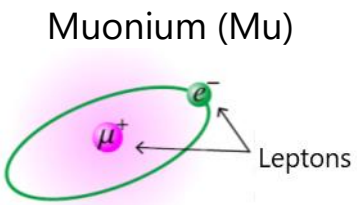
As of 25 May 2023



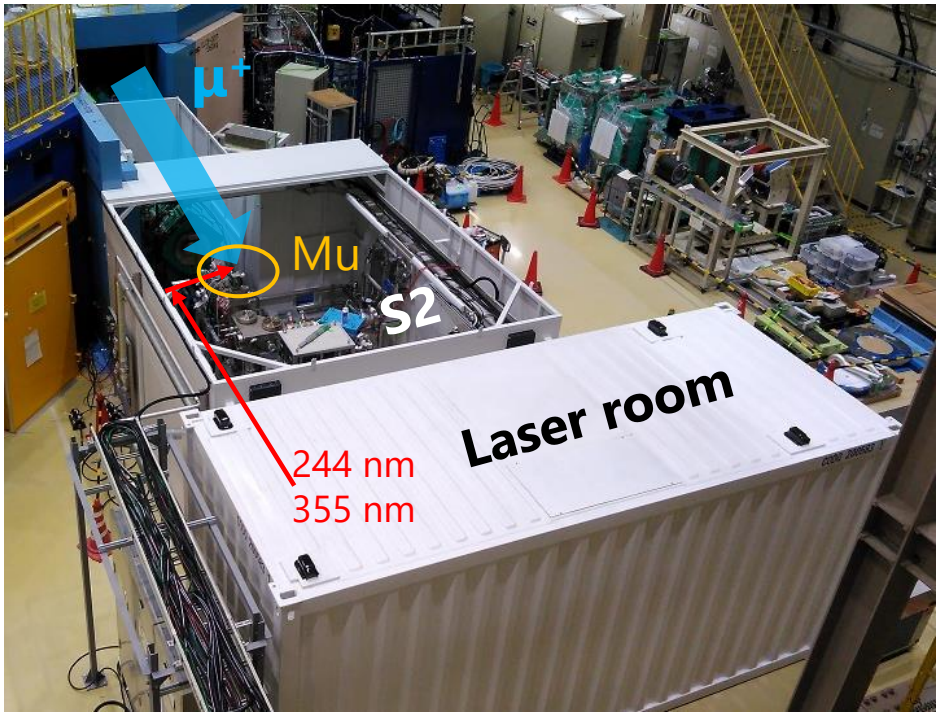
Future extension to accelerate up to 212 MeV

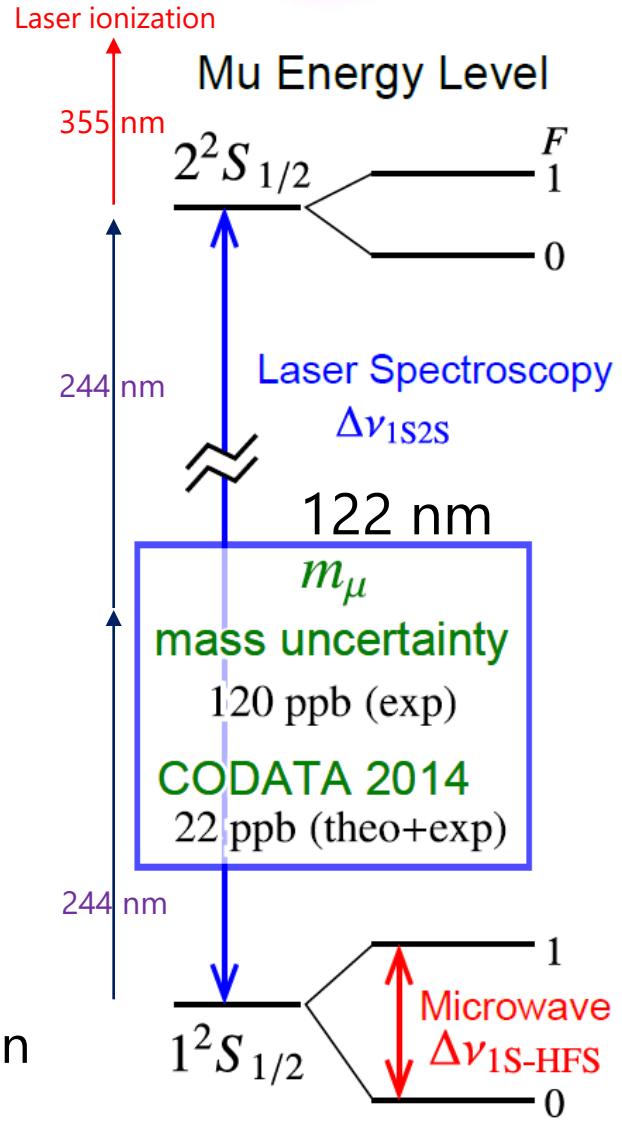
For muon g-2/EDM and transmission muon microscope

S2 area and Mu 1S-2S



- 2nd branch of S line for Mu 1S-2S spectroscopy
  - ✓ Surface muon beamline: 2×10^6 μ^+/s
  - ✓ In operation since FY2021

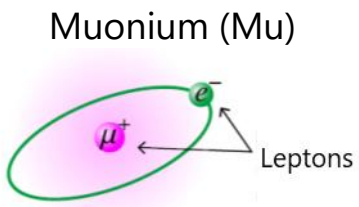




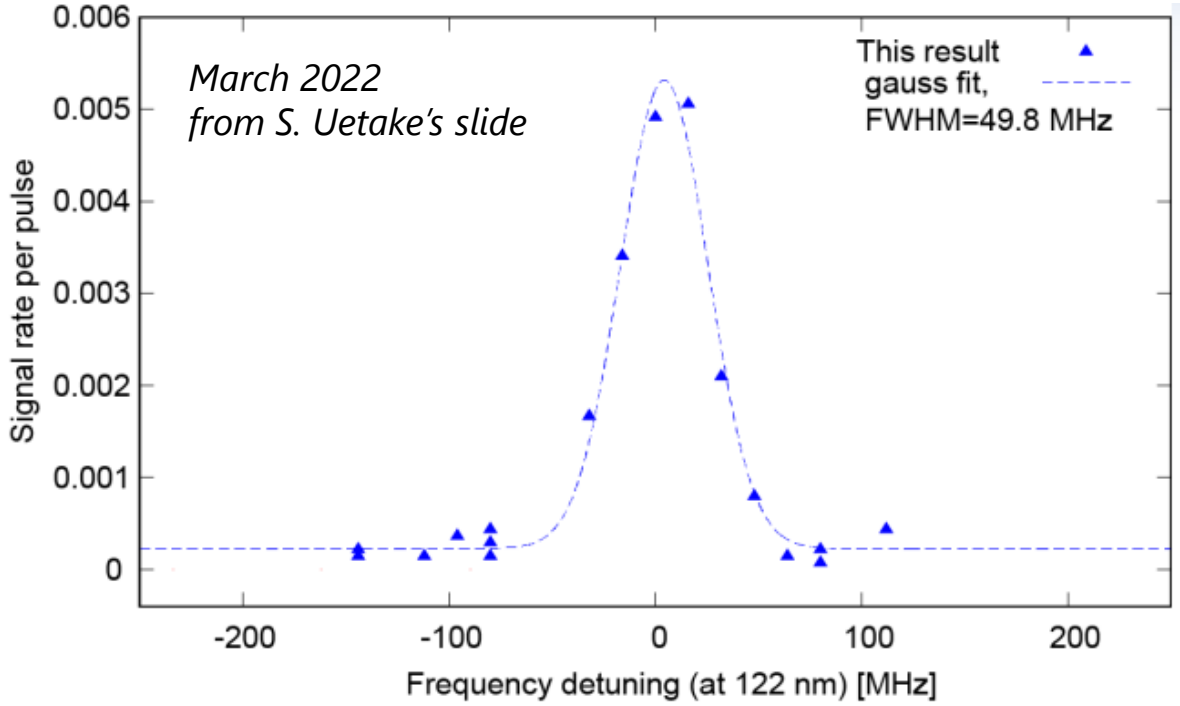
$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{\underbrace{m_\mu}_{\text{mass}}}\right)^{-1}$$

Goal:
10 kHz precision
Δm_μ = 1 ppb

S2 area and Mu 1S-2S



- Resonance signals were successfully observed in early 2022.
- Efforts are currently being made to reduce systematic errors.



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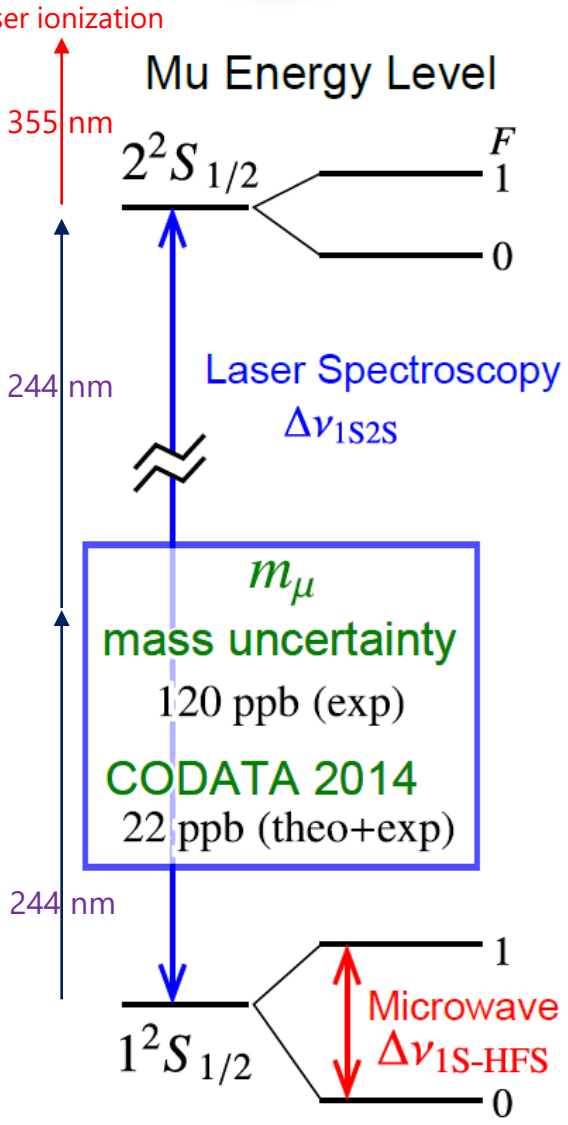
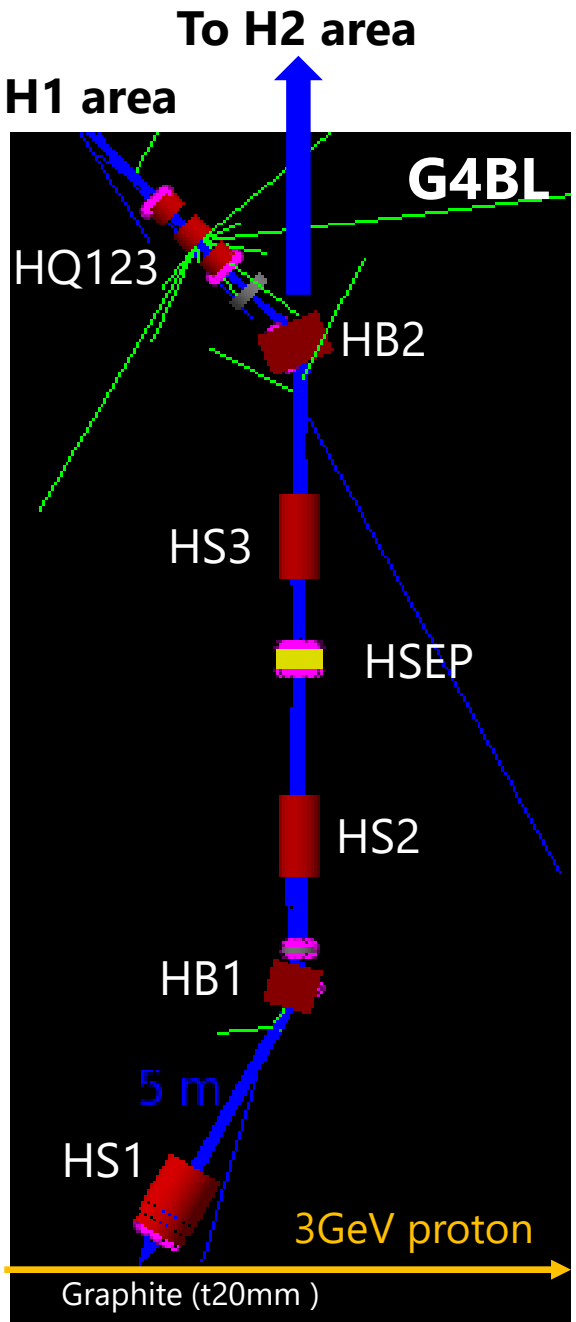
mass

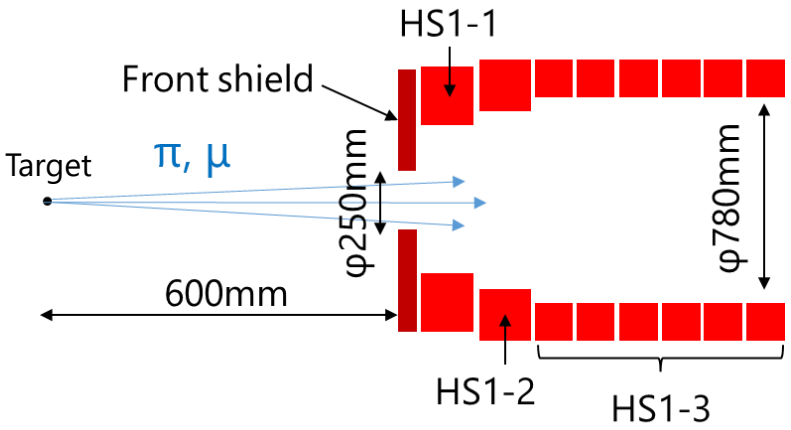
Goal:
10 kHz precision
Δm_μ = 1 ppb



H line



- H line is a high intensity muon beamline which can deliver both of surface μ^+ and cloud μ^+/μ^-.
- Beamline optics
  - HS1 : large acceptance capture solenoid



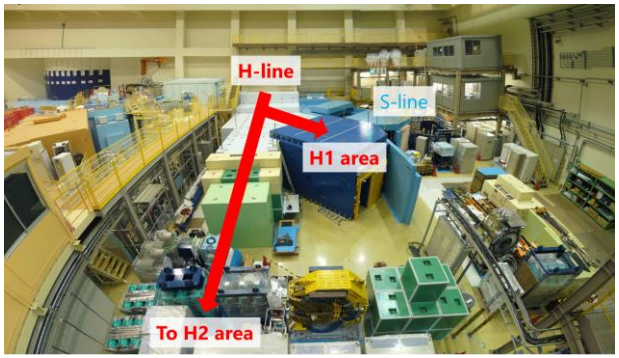
Spec.
HS1-1 : 0.37T
HS1-2 : 0.31T
HS1-3 : 0.60T
*Normal conducting
*Good radiation resistance (MIC)

  - HS2,3 : Two superconducting solenoid with opposite polarities
  - HSEP : Wien filter to reduce e^+/e^- background → will be installed during the next summer shutdown
- Surface muons of 10^8 μ^+/s @1 MW
- **First beam to H1 area on 15 Jan. 2022!**

H-line construction history

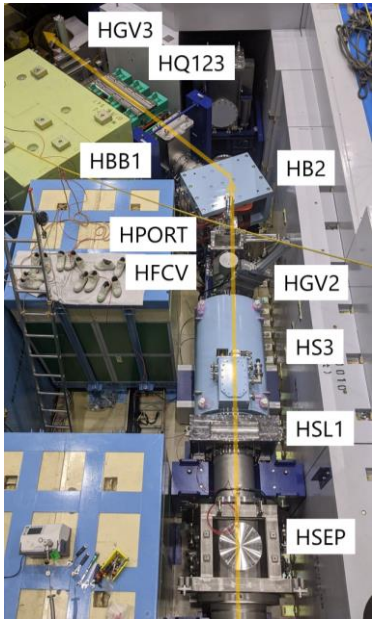
JFY2012
Frontend devices

JFY2016 Radiation shield

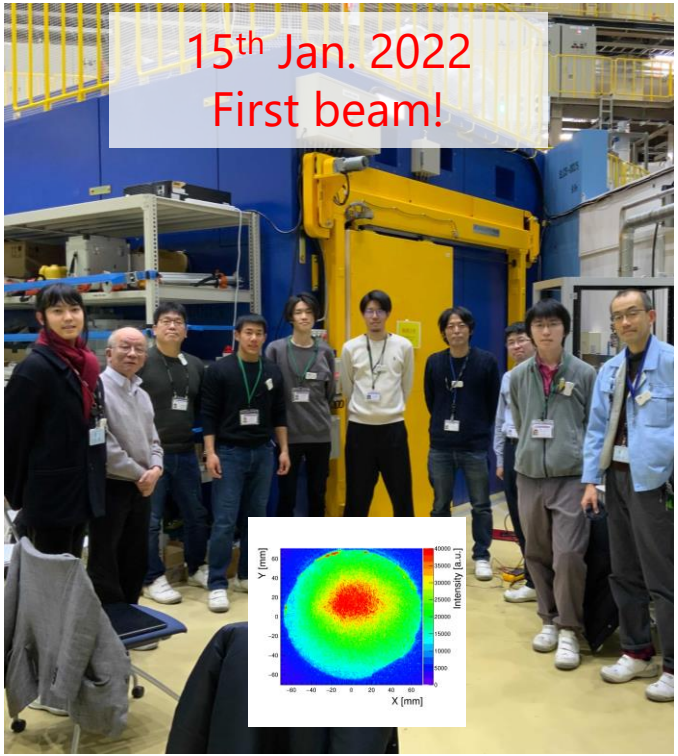


JFY2017~2019: Electric sub-station
* For the NC capture solenoid

JFY2020
Install magnets

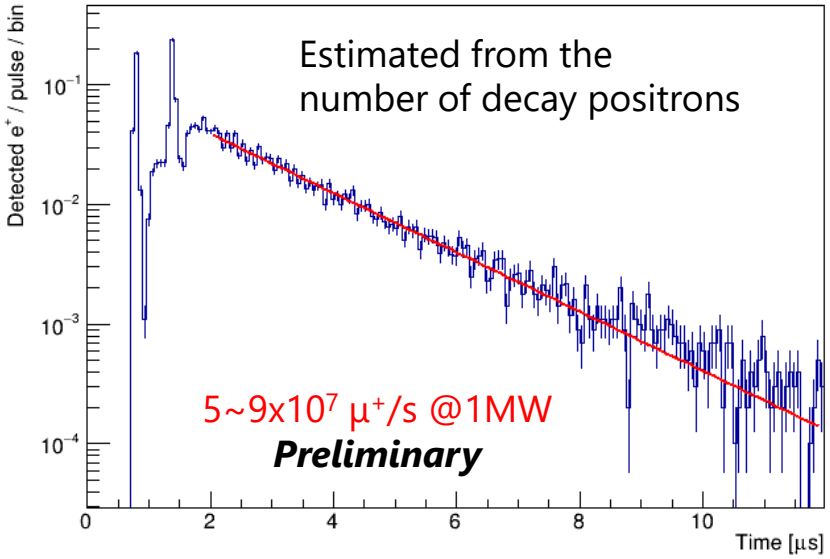


JFY2021
Cabling, plumbing

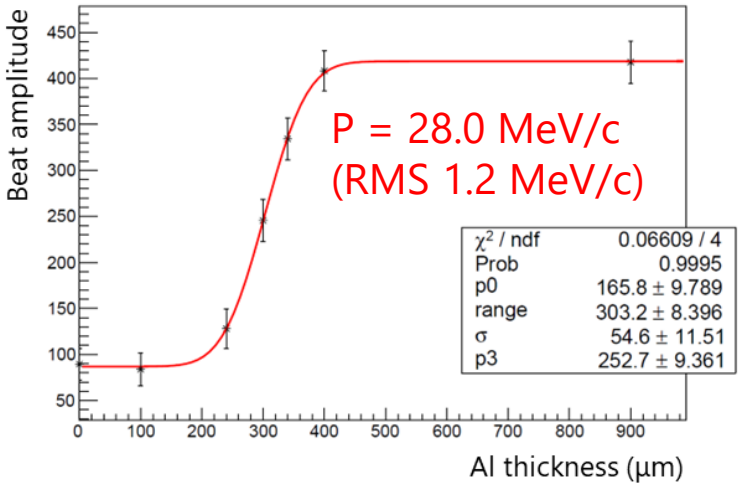


H-line commissioning

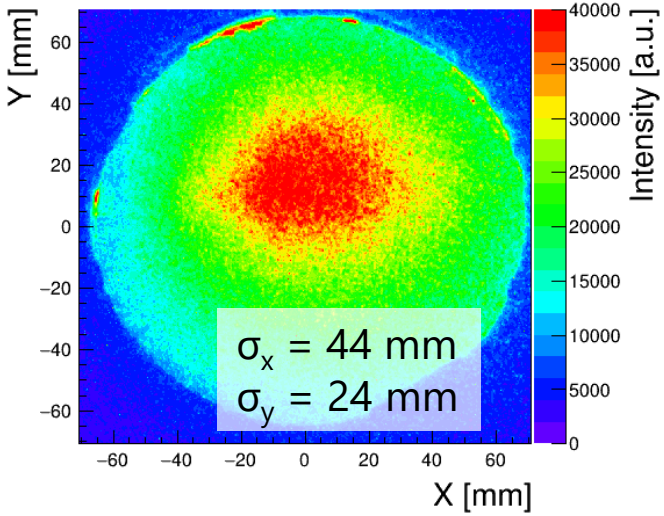
Surface muon intensity



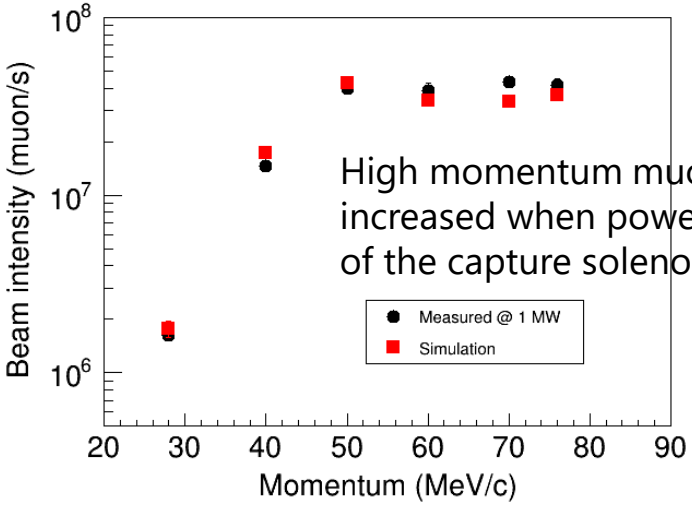
Momentum of surface muons
estimated from μ⁺ range in Al target



A typical profile of surface μ⁺



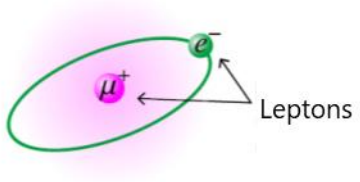
Negative (cloud) muon intensity



High momentum muons will be increased when power supplies of the capture solenoid are fixed.

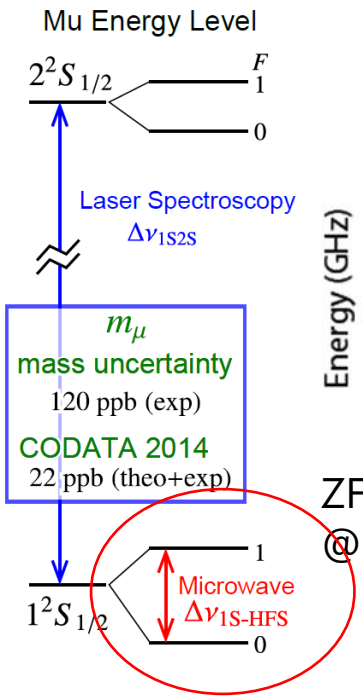
Mu HFS @H1 area

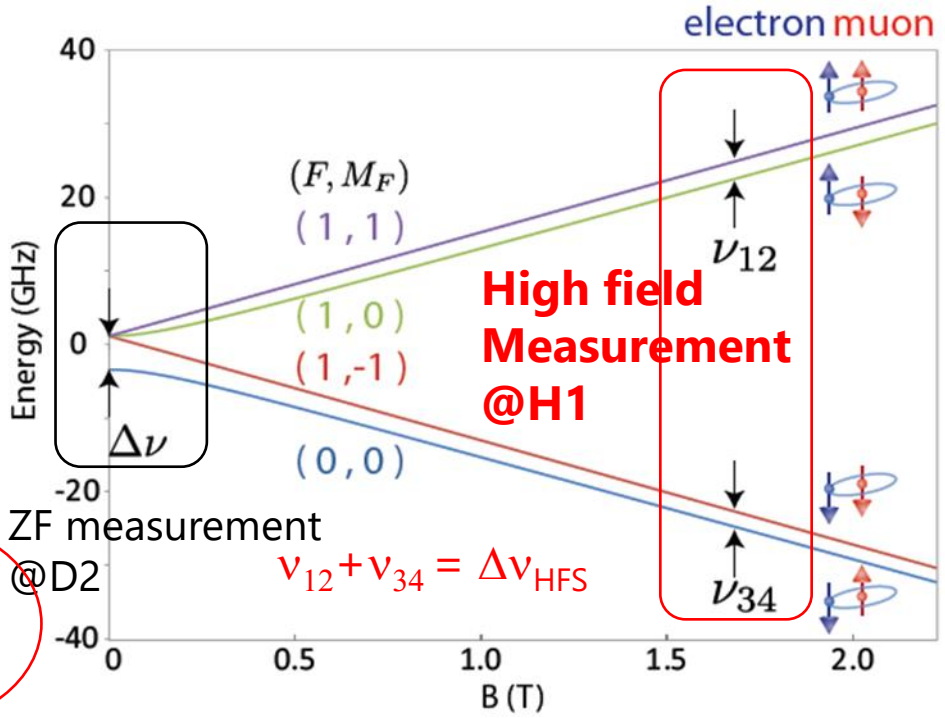
Muonium (Mu)



→ Iwai-san's talk

- Precise measurement of the hyperfine structure of muonium
- MuSEUM: **Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave





ZF measurement @D2

$\nu_{12}+\nu_{34} = \Delta\nu_{HFS}$

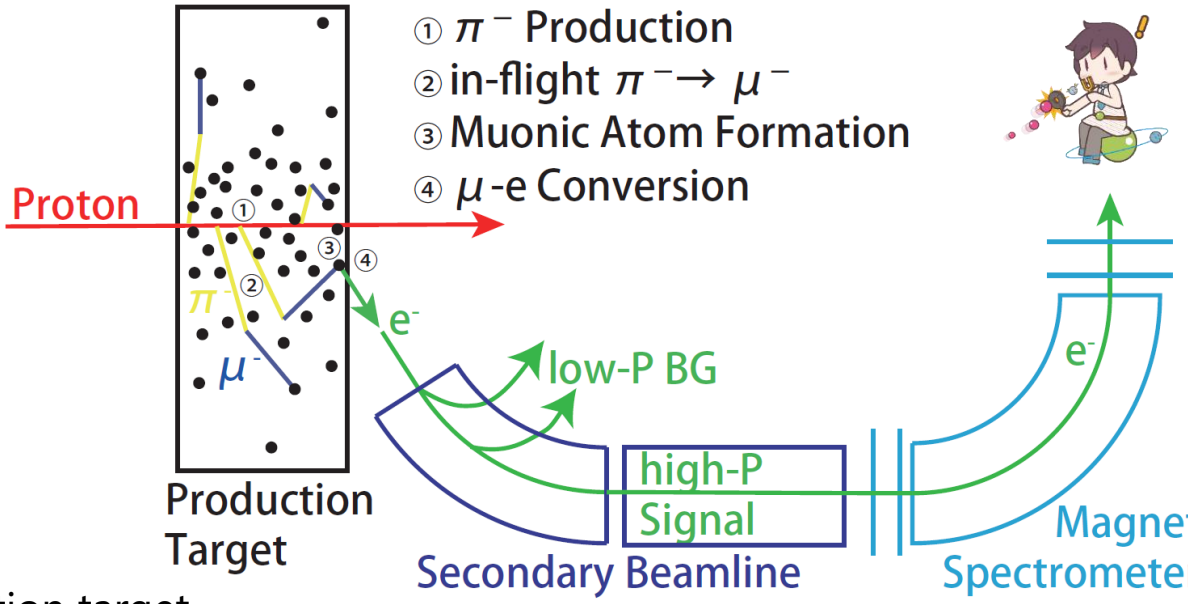
Previous experiment: 4 463.302 765 (53) MHz (LAMPF1999)

Precision of 8 Hz will be reached by a high field measurement at the H-line.

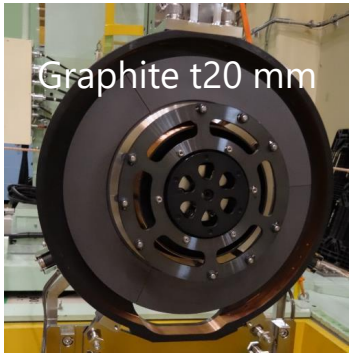
This experiment is going to conducted after the Wien filter is installed.

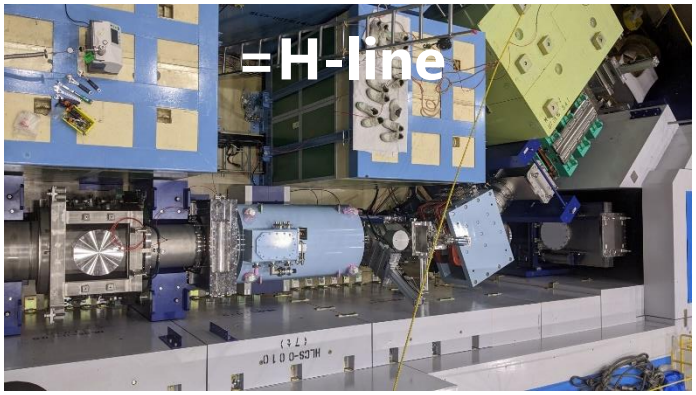
$\mu^-N \rightarrow e^-N$ @H1 area

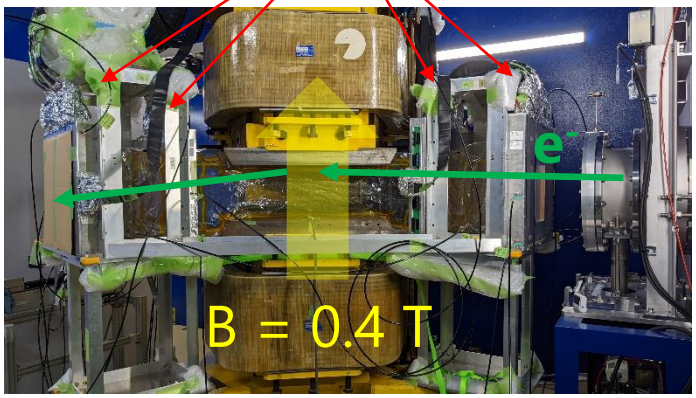
- Search for μ-e conversion (sensitivity ~10^{-14})
  - DeeMe: **D**irect **e**lectron **e**mission from **M**uon **e**lectron conversions
  - Detectors are installed in H1 area and pilot RUN is underway.



Production target







Future extension of H line

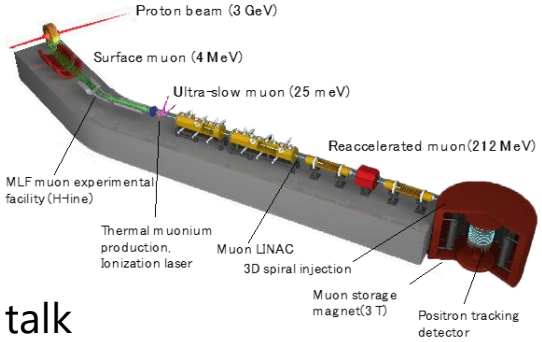
Extension of H line

At the 2nd branch of H line, ultra-slow muons will be re-accelerated up to 212 MeV to obtain a low-emittance (1 π mm*mrad) muon beam.

Muon g-2/EDM experiment

▷ The low-emittance muon beam enables us not to use a strong focusing E-field.

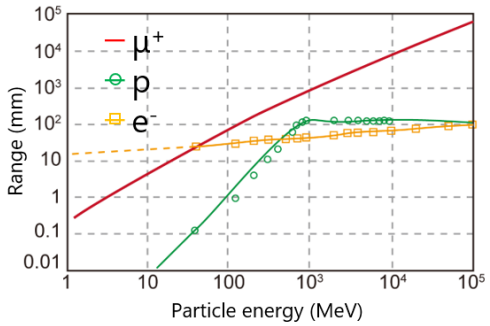
▷ Complementary method to check the discrepancy

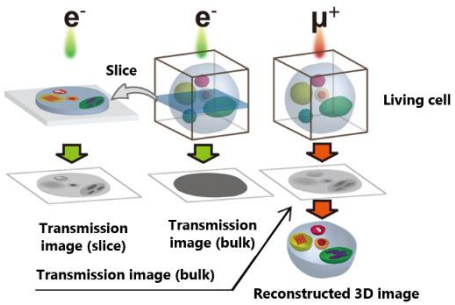


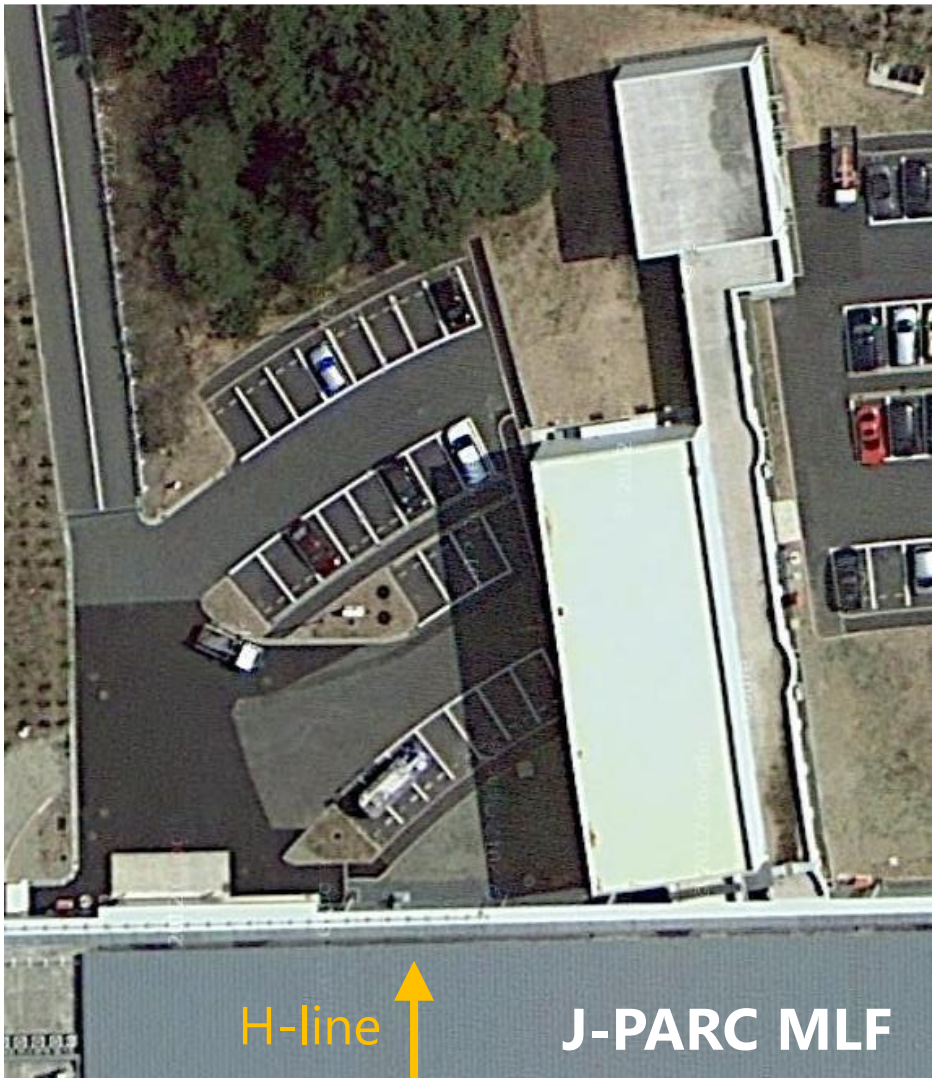
→Gerco-san's talk

Transmission muon microscope (TμM)

▷ Observe bulk samples utilizing the strong penetrative power of re-accelerated muons







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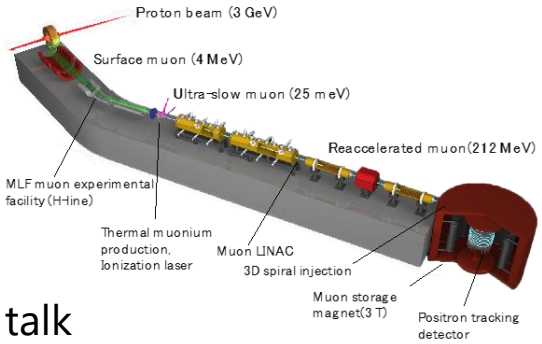

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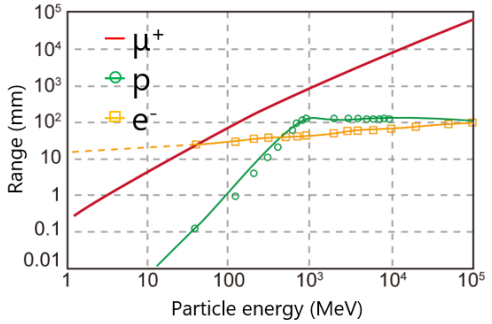
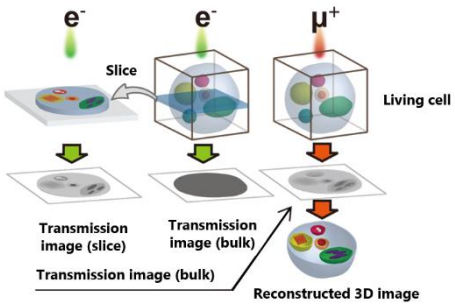
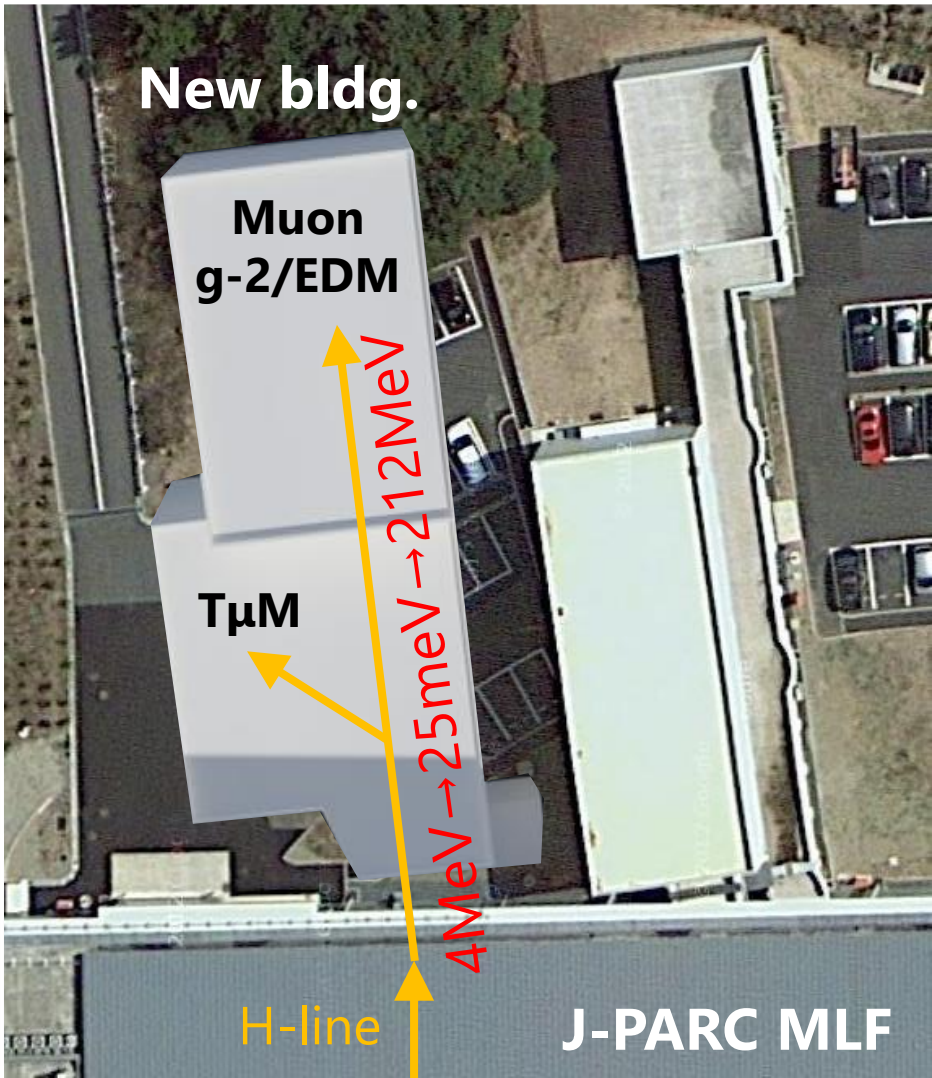
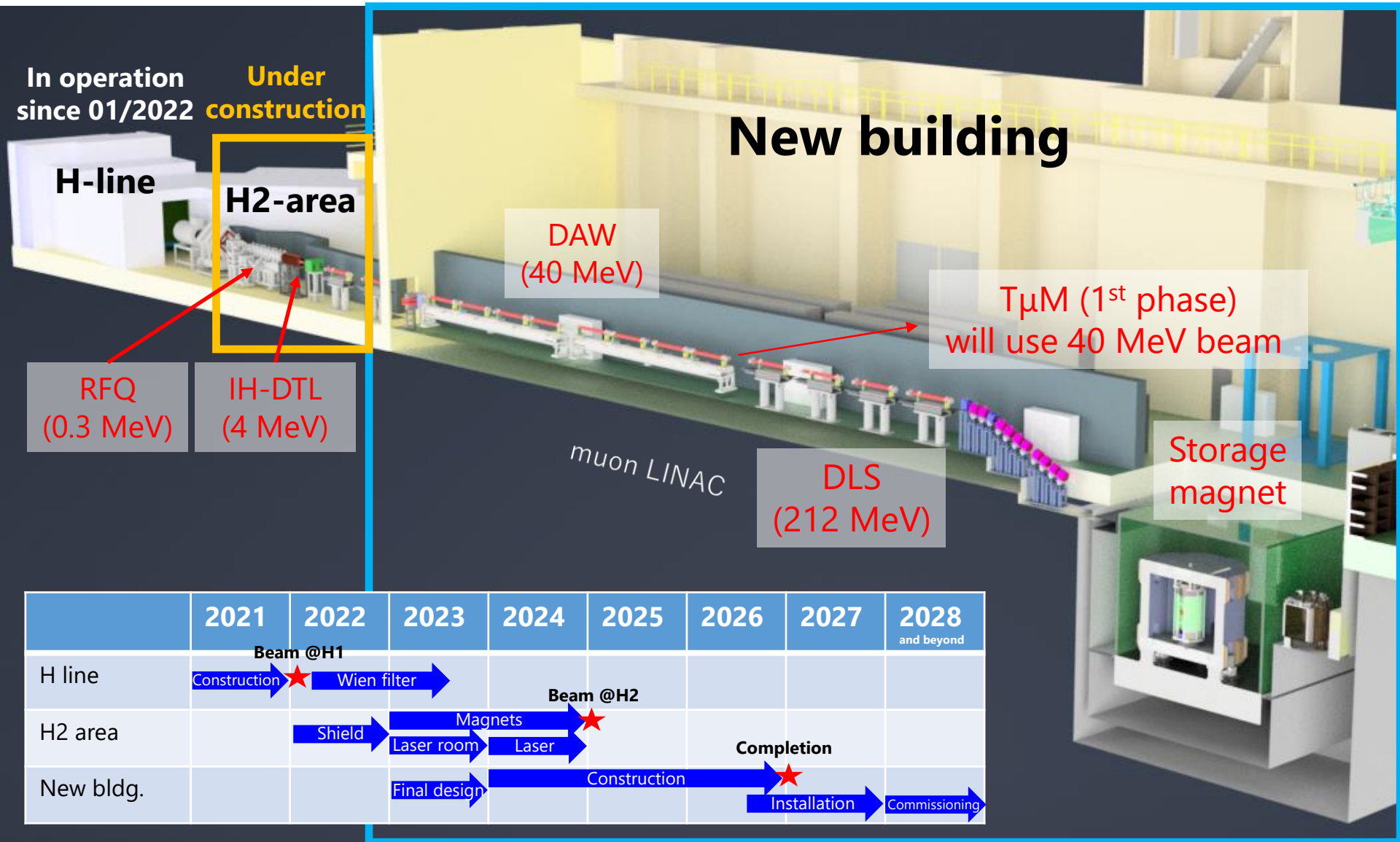




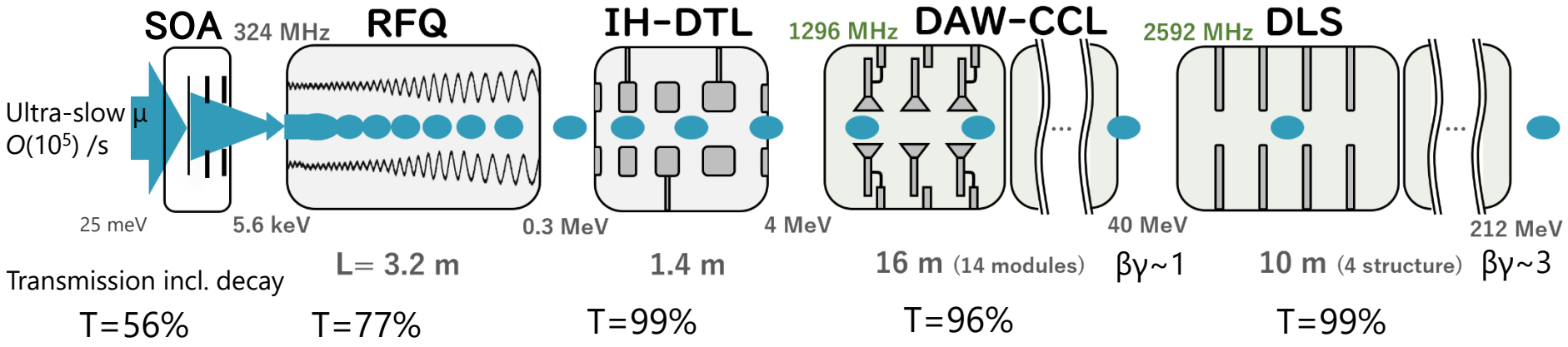


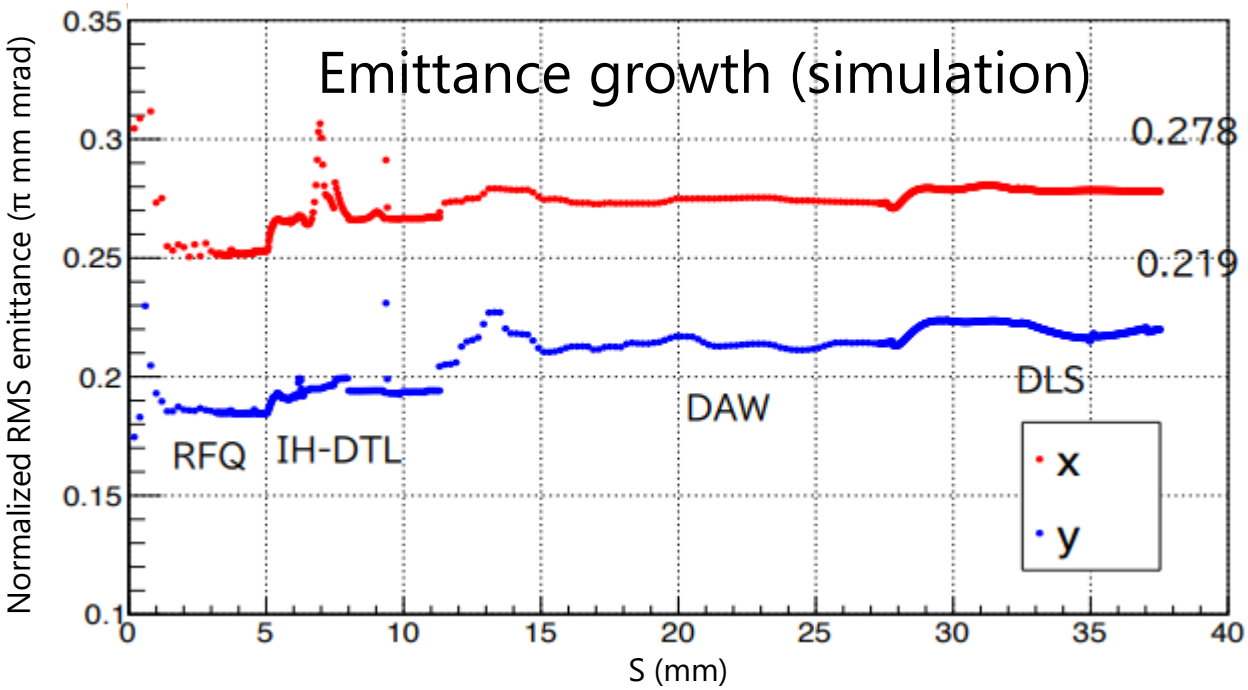
H-line experimental bldg.



	2021	2022	2023	2024	2025	2026	2027	2028 and beyond
H line	Beam @H1 ★ Construction	Wien filter			Beam @H2 ★			
H2 area		Shield	Magnets / Laser room	Laser		Completion ★		
New bldg.			Final design	Construction		Installation	Commissioning	

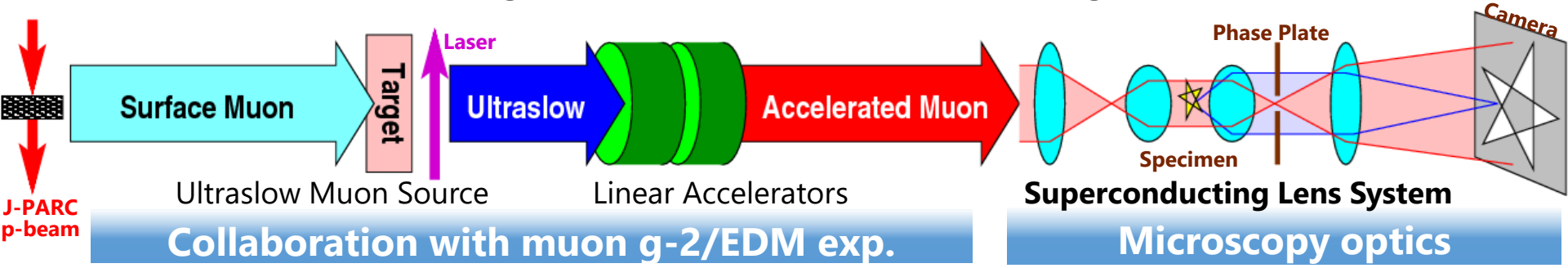
Low emittance muon beam





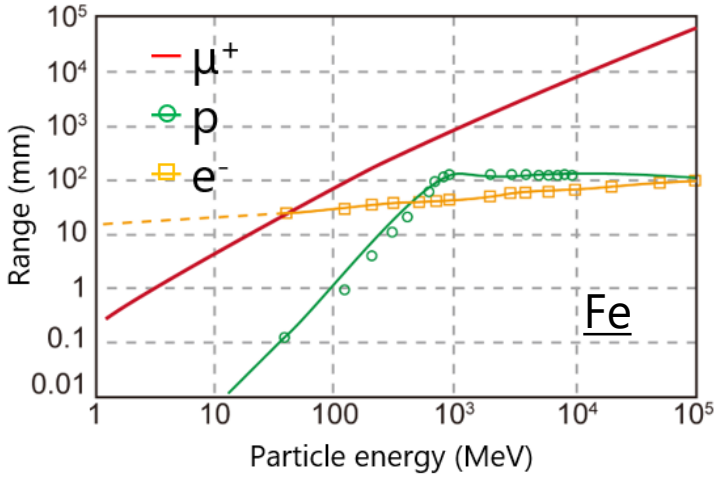
Transmission Muon Microscope

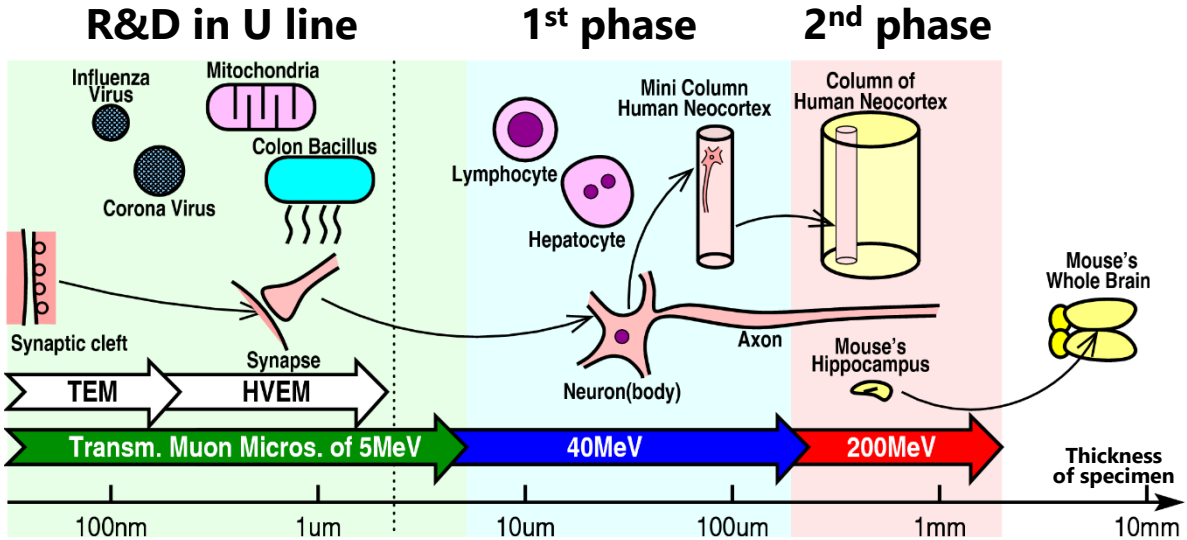
= Accelerated Muon : Strong Penetration + Ultraslow Muon : High Luminance / Resolution



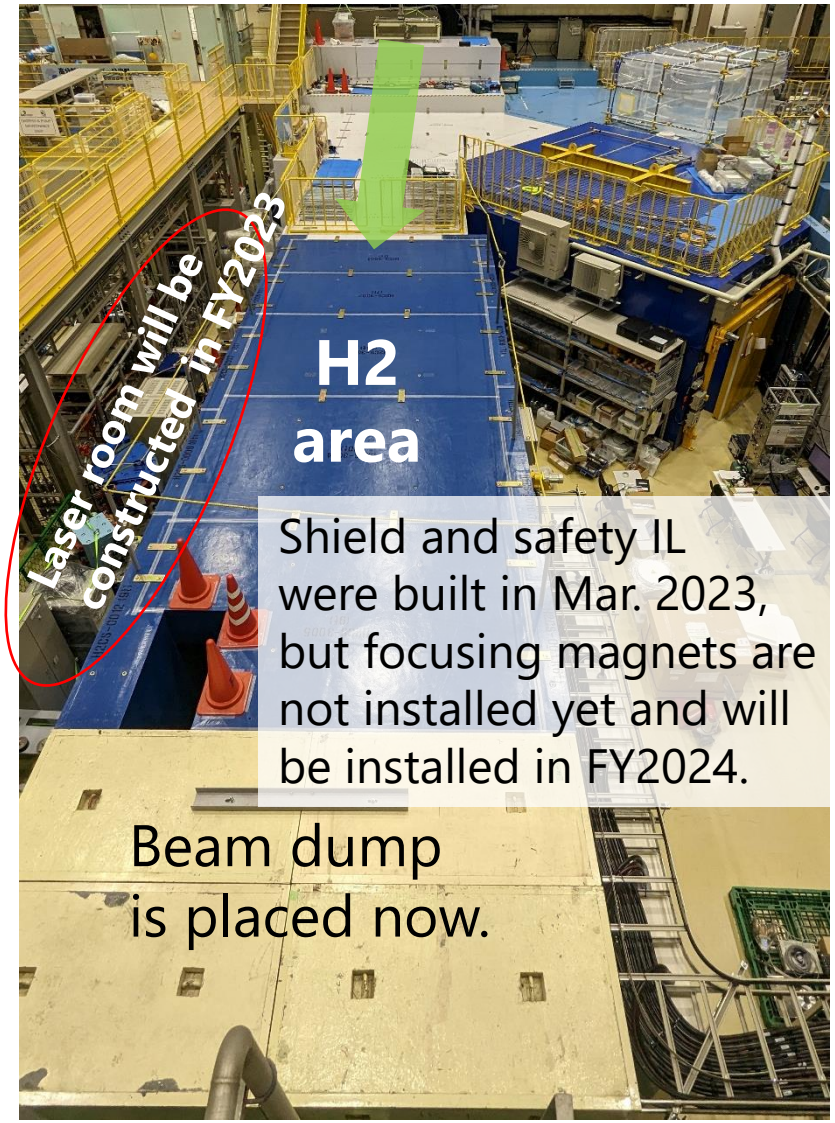
Observe bulk samples utilizing the penetrative power of re-accelerated muons

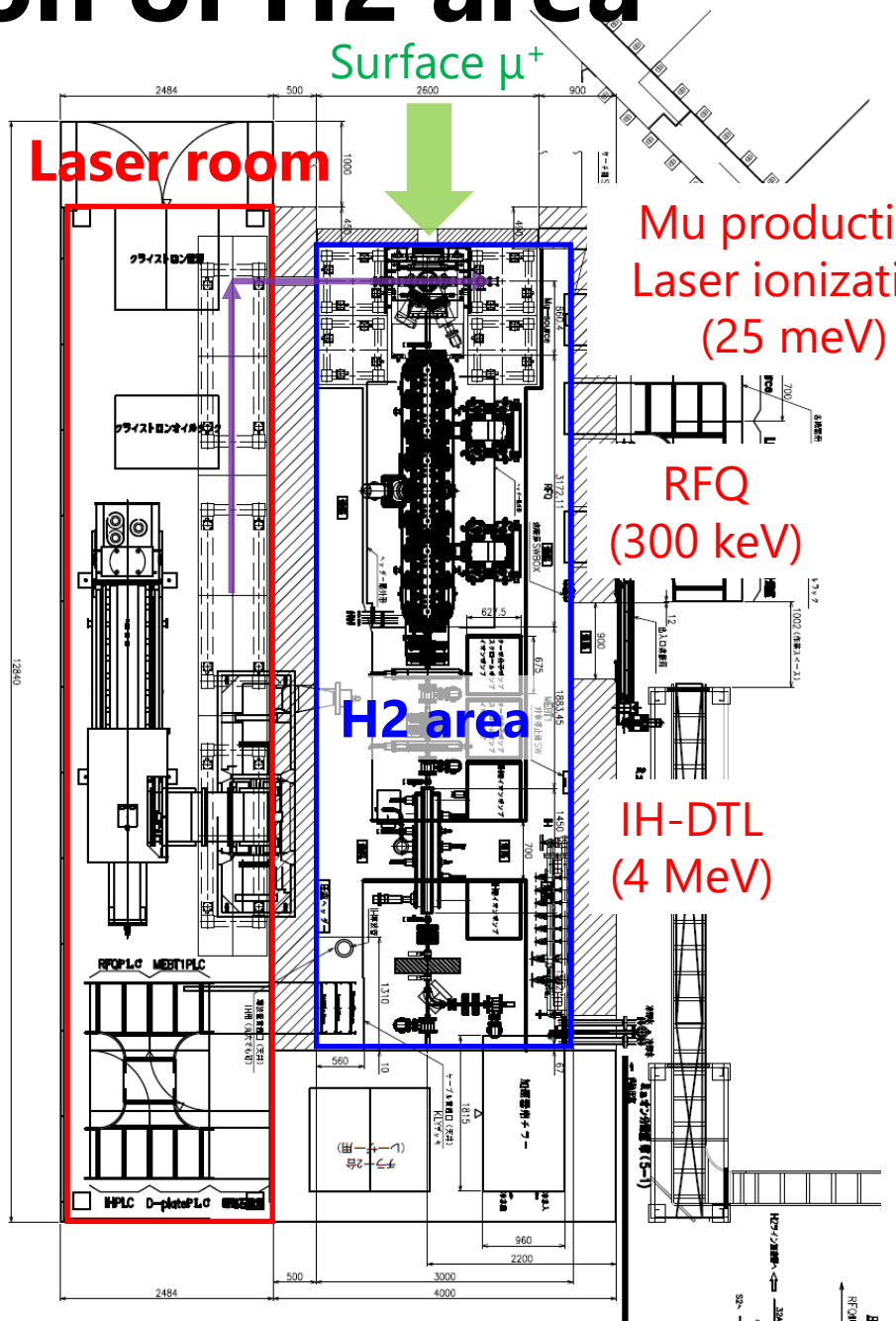
- Any methods for TEMs are applicable
- Functional imaging of living/cryo-tissues
- It can see EM fields in packaged IC/LSI, Li ion battery, solar cell, piezo, etc.



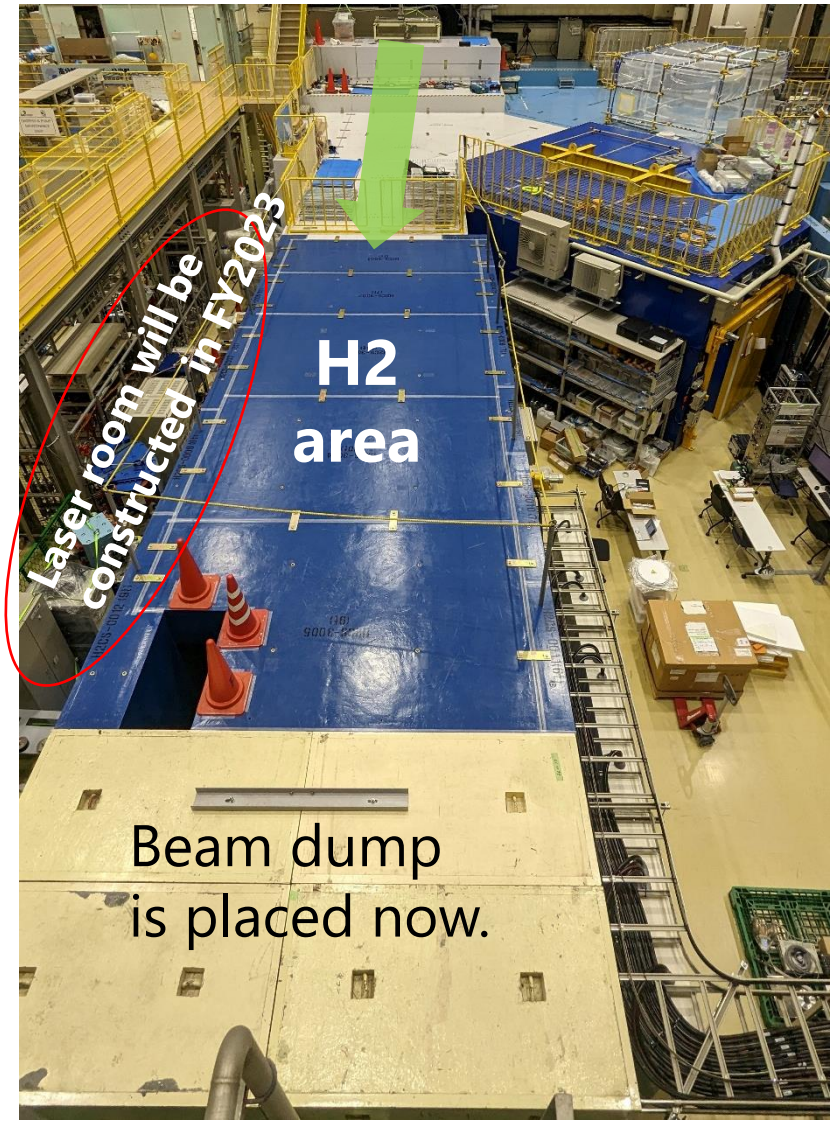


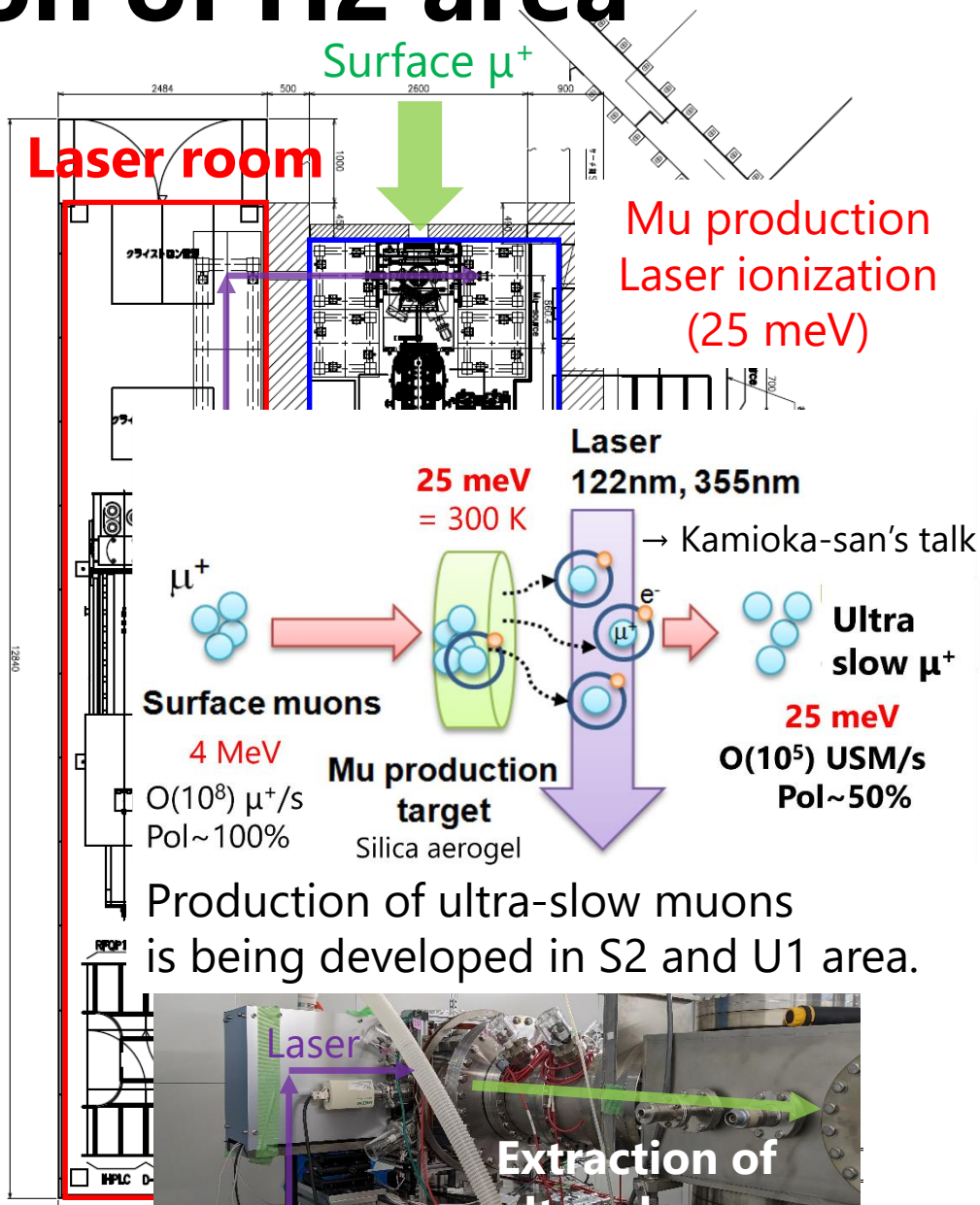
Construction of H2 area



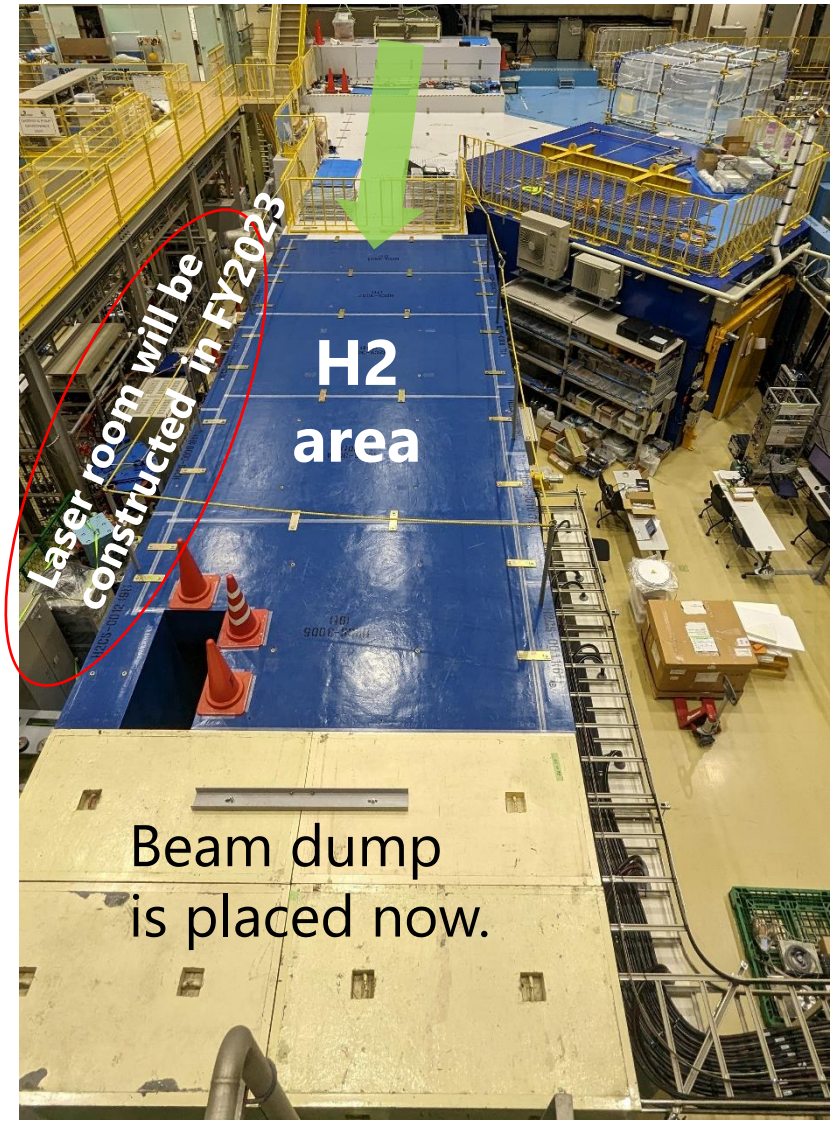


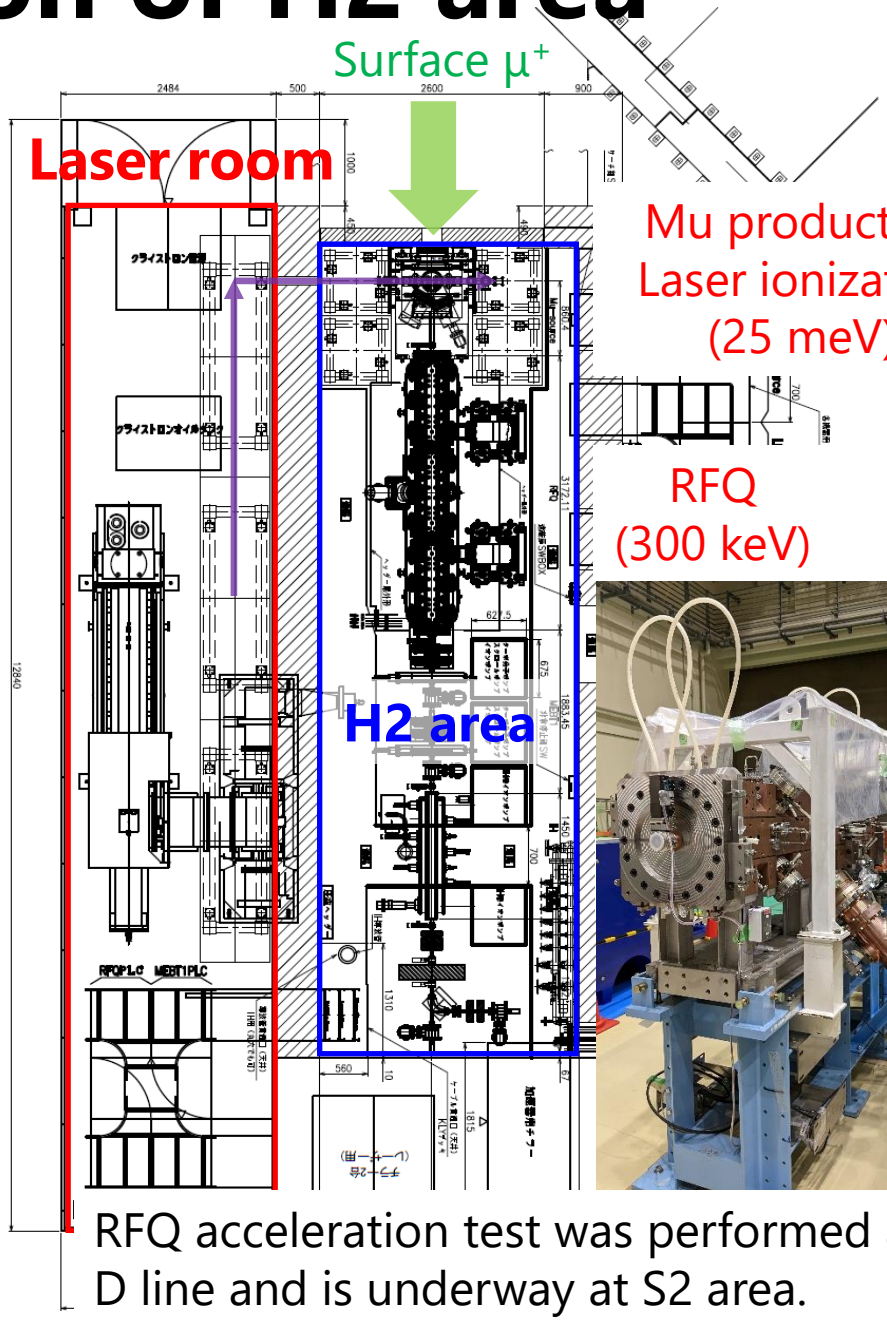
Construction of H2 area





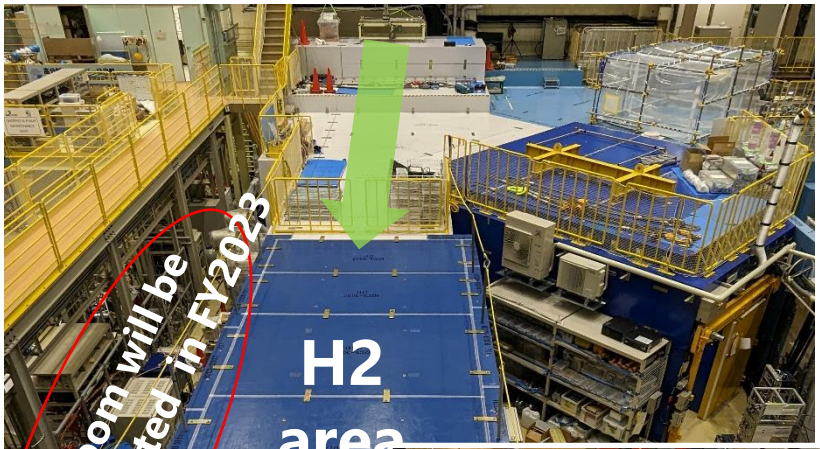
Construction of H2 area

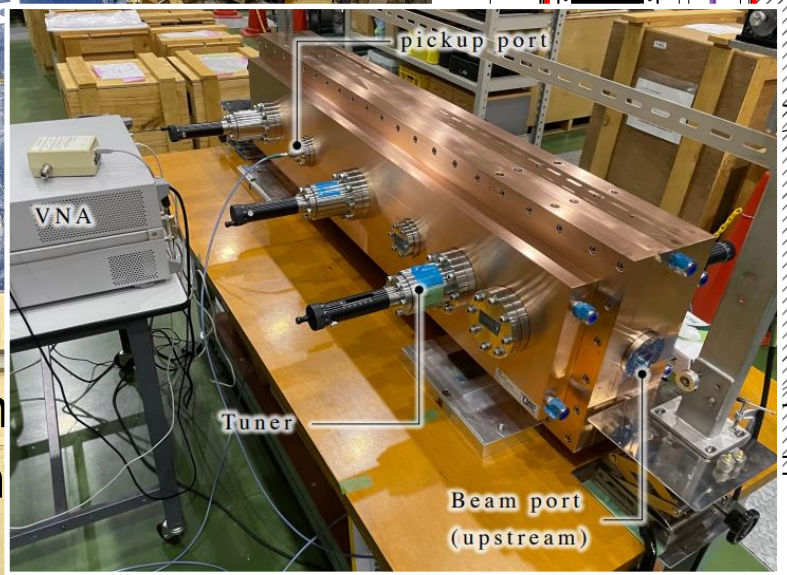


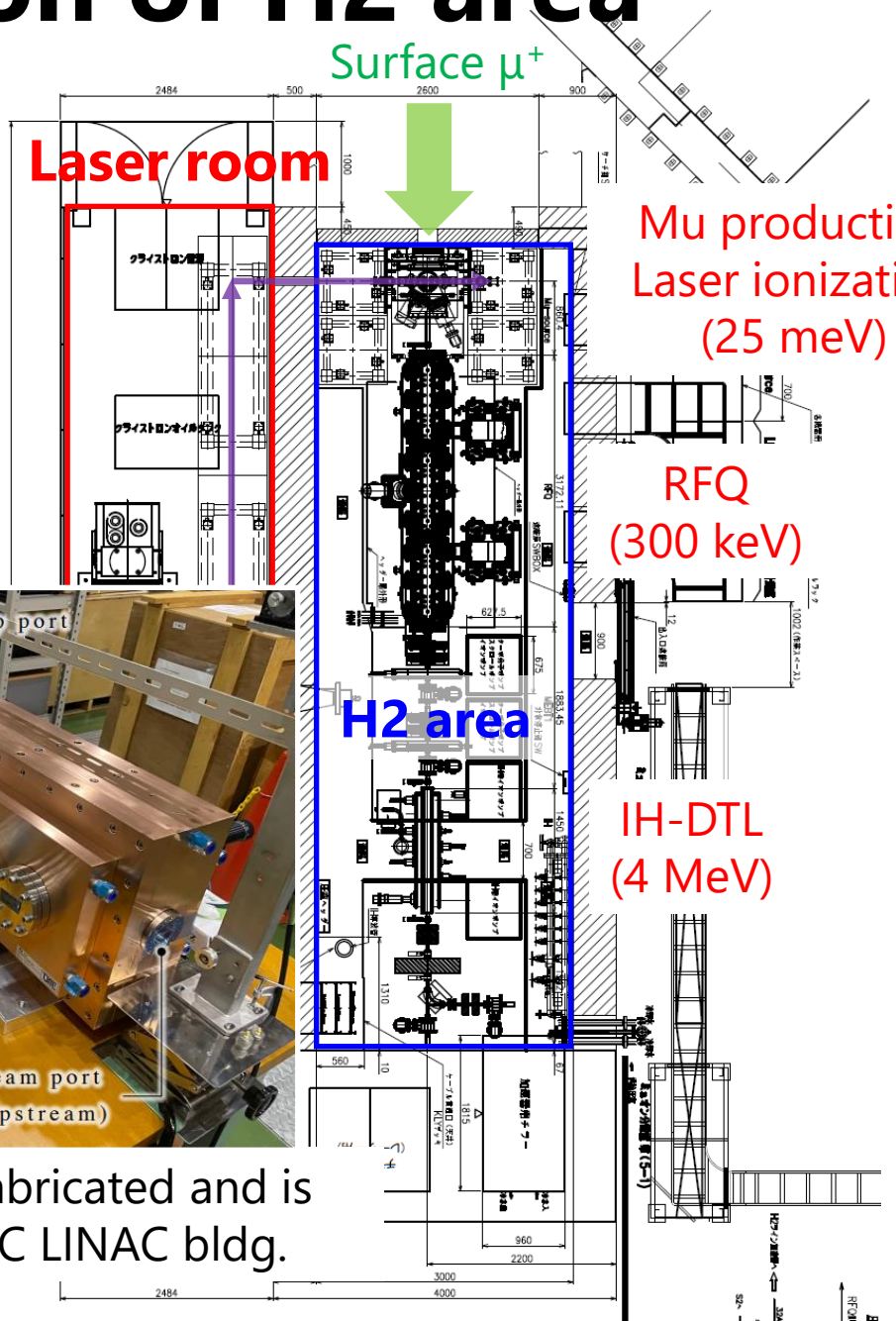


RFQ acceleration test was performed at D line and is underway at S2 area.

Construction of H2 area





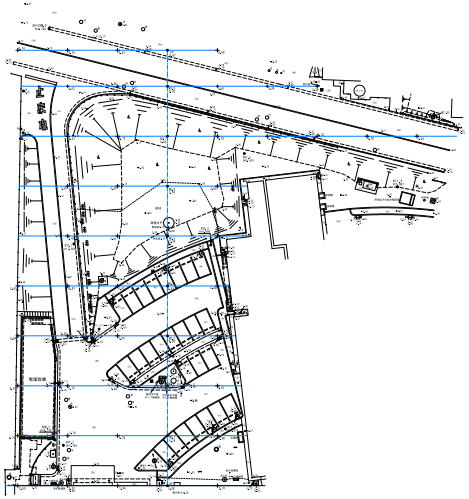


IH-DTL was already fabricated and is being tested in J-PARC LINAC bldg.

Preparatory works for new bldg.

Geotechnical investigation

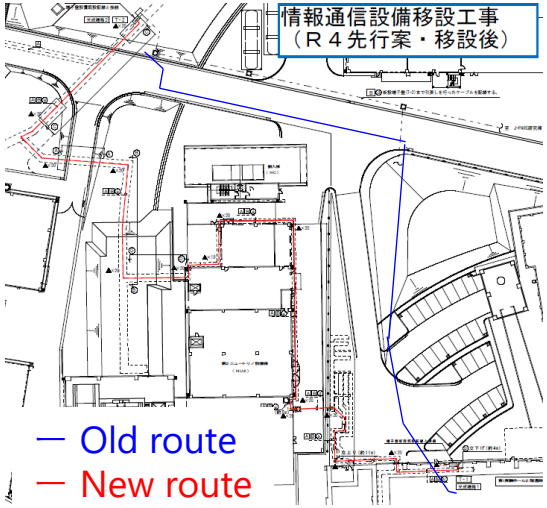
Survey of the construction site



Research of buried cultural properties

No buried cultural properties were found.

Relocation of buried cables

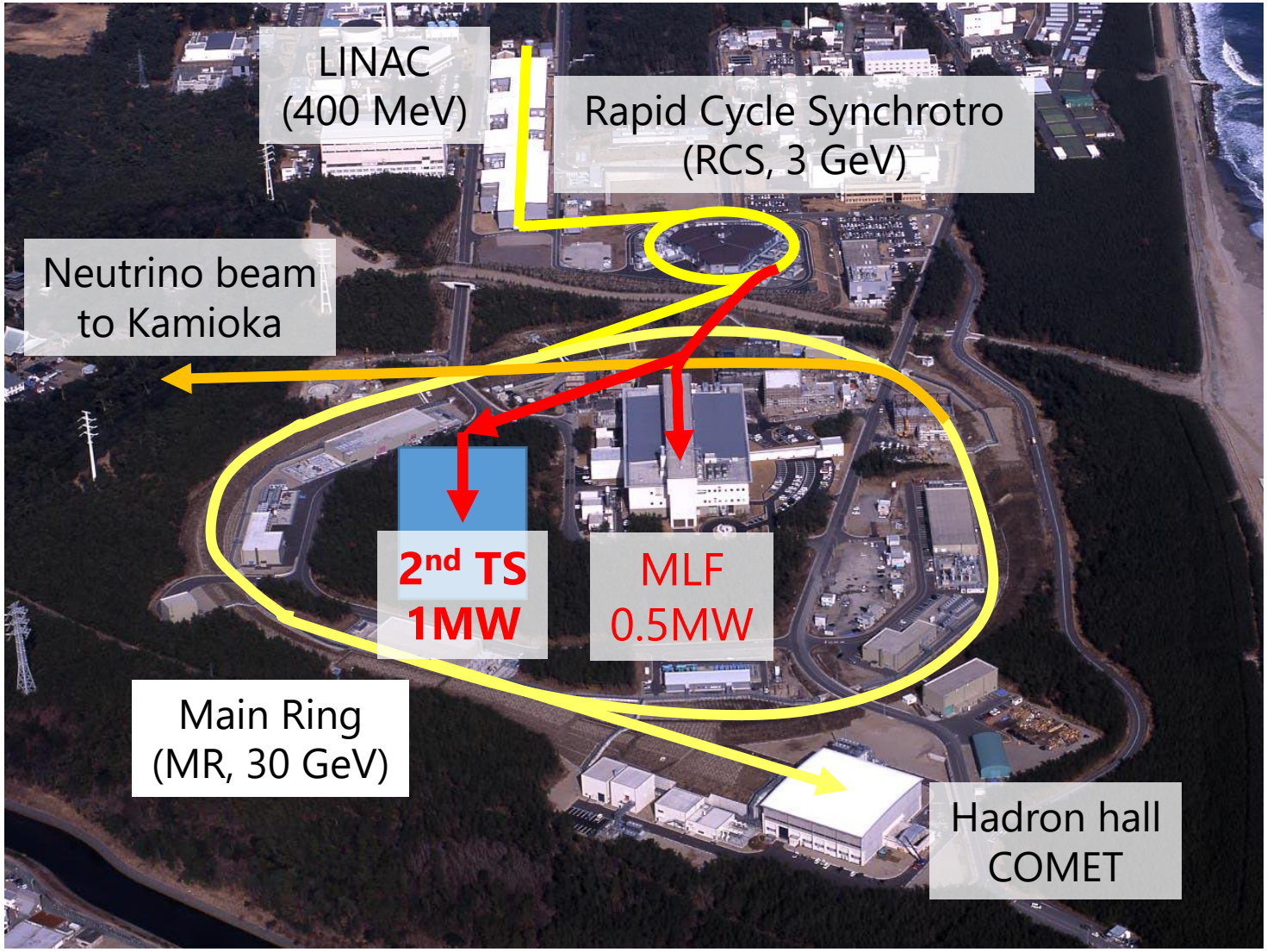


Detailed design is going to be finalized in FY2023 to begin construction next year.

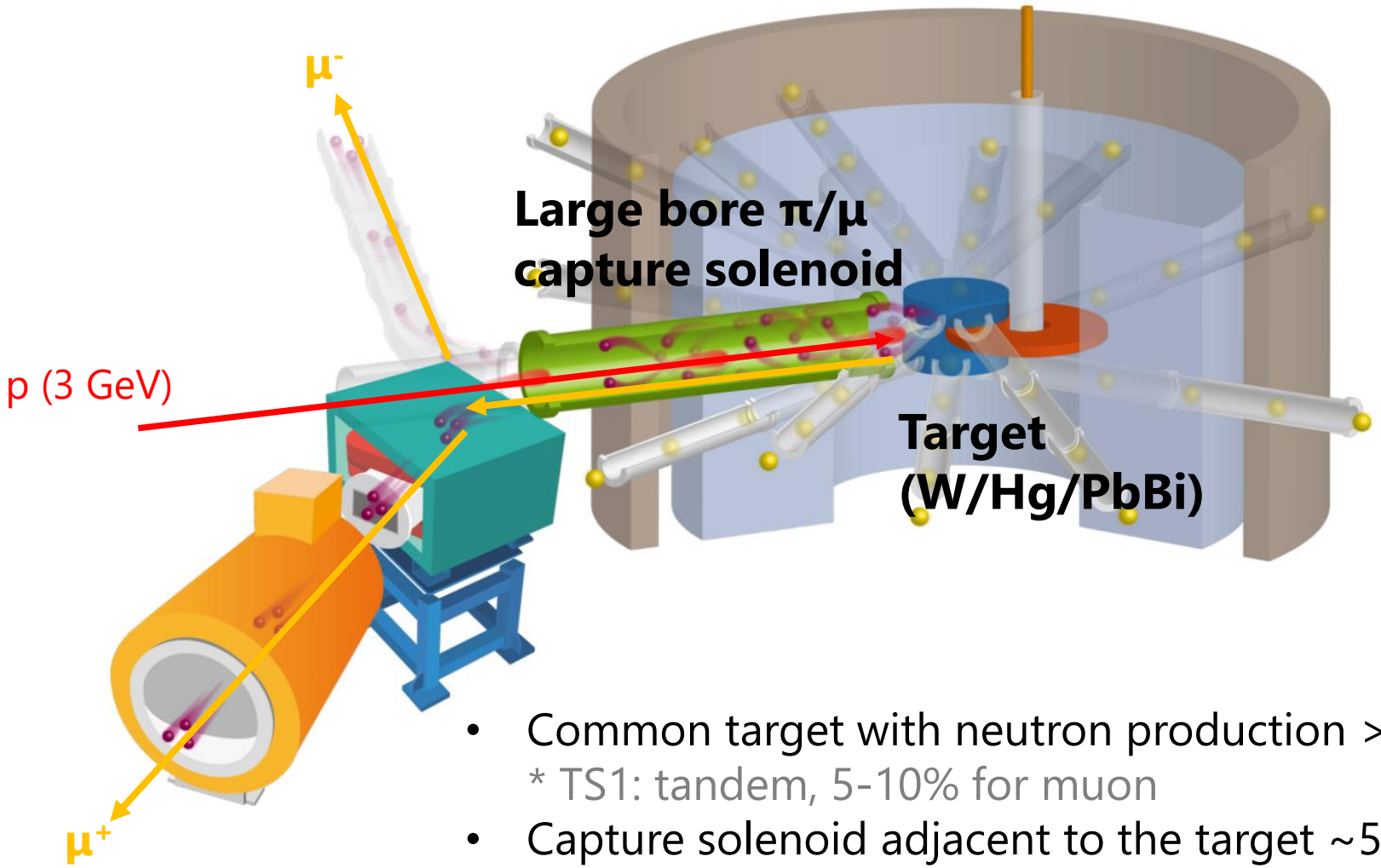
Future program: 2nd target station

J-PARC MLF 2nd target station

Conceptual Design report v1.2



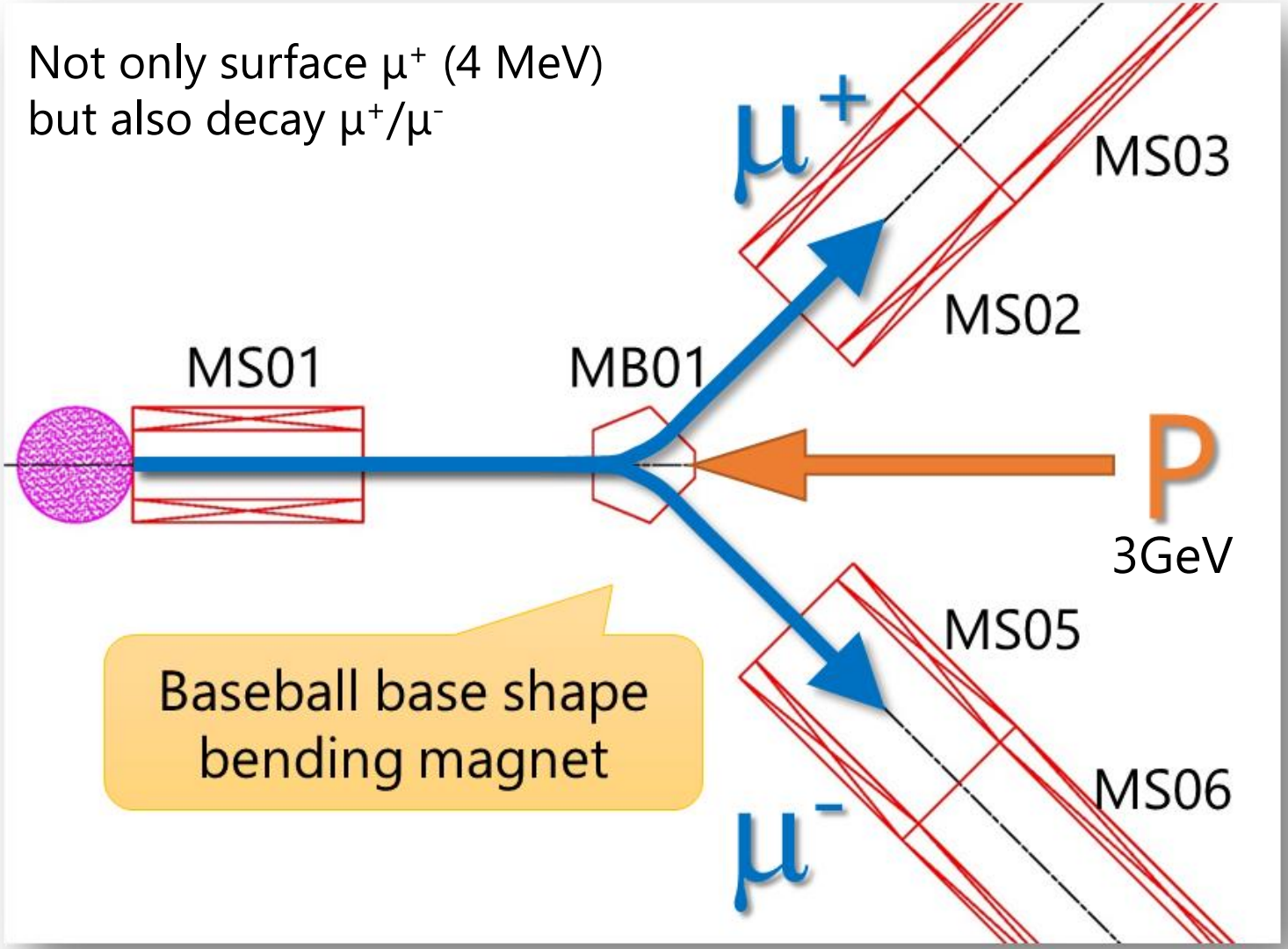
Conceptual design



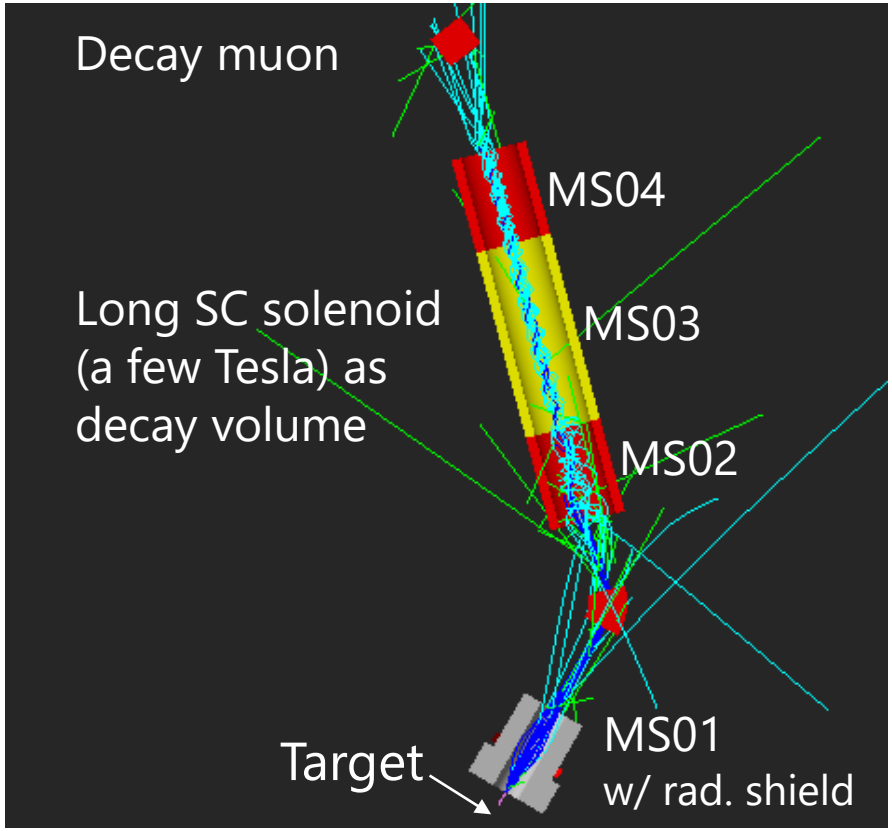
- Common target with neutron production >10x
  * TS1: tandem, 5-10% for muon
- Capture solenoid adjacent to the target ~5x

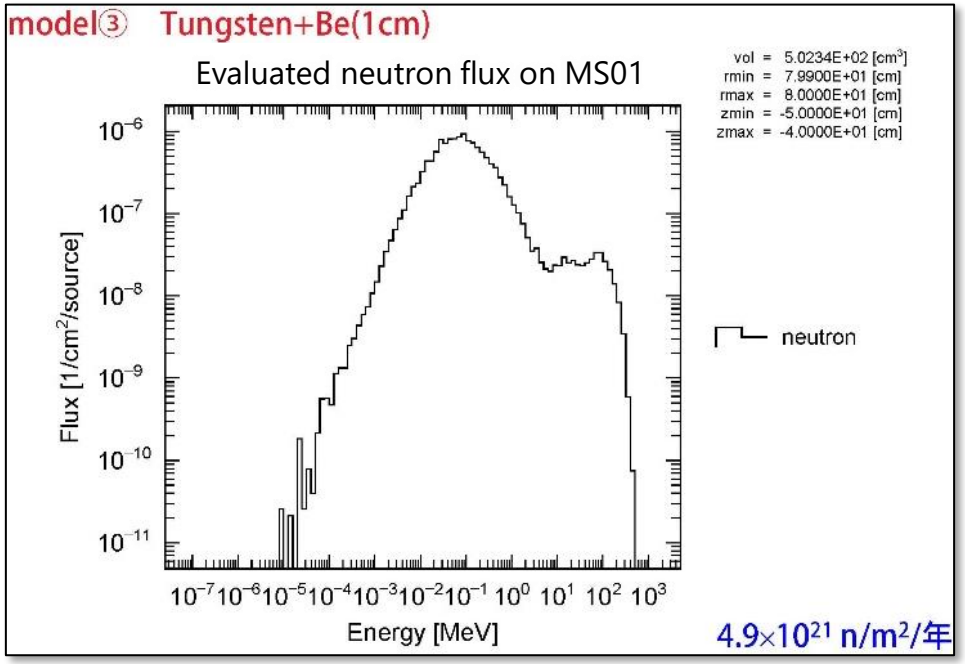
>50 times higher intensity of surface μ~10^{10} μ/s

Simultaneous extraction of μ^+/μ^-



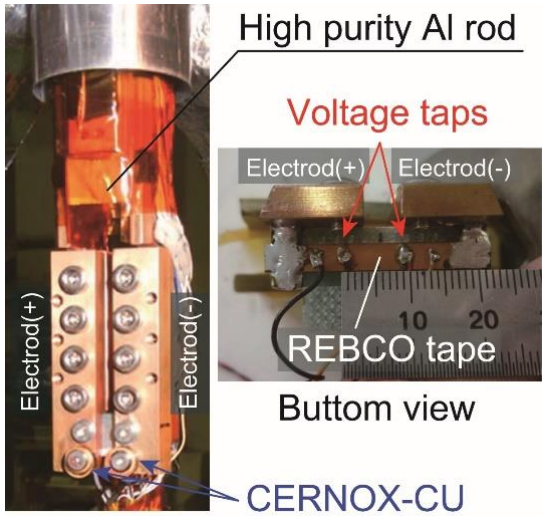
Design of the frontend magnet





Studying with Prof. Ogitsu (KEK cryo center) and COMET group, use of a SC coil at the capture solenoid (MS01) was confirmed to be possible.

Irradiation test has been performed to the candidates of SC material (HTS).
T. Ogitsu *et al.*, Instruments 4 (2020) 30,
DOI: 10.3390/instruments4040030



Summary

- New beamlines for fundamental physics joined the J-PARC muon facility recently.
  - H-line is a high intense muon beamline (surface μ^+ ~10^8 /s)
  - H1 and S2 areas in operation

- Extension of H line to produce low emittance beam is ongoing.
  - FY2024: Ultra-slow muon production at H2 area
  - Construction of the new building for muon g-2/EDM and TμM could start next year (depends on budget situlation)

- Conceptual design of the 2nd target station of the MLF is in progress.

Backup slides

New target

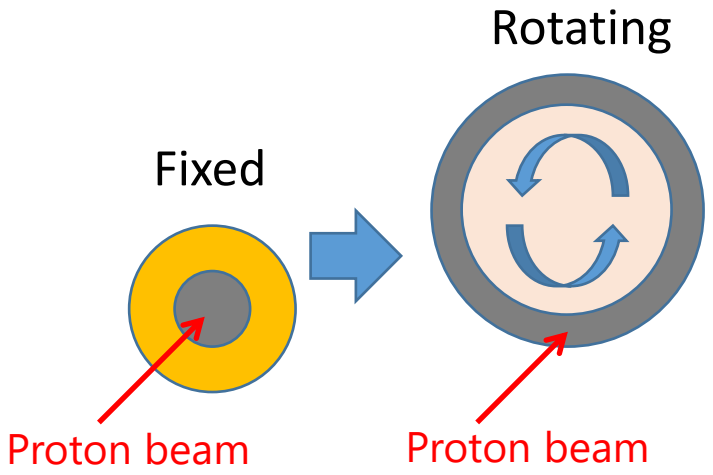
- Target and capture solenoid are the most important to get intense muon beam.
  - Near future: replace current target to enhance surface muons >2x → MuSEUM, DeeMe, 1S-2S, g-2/EDM
  - Future (10-20 years): target development for TS2

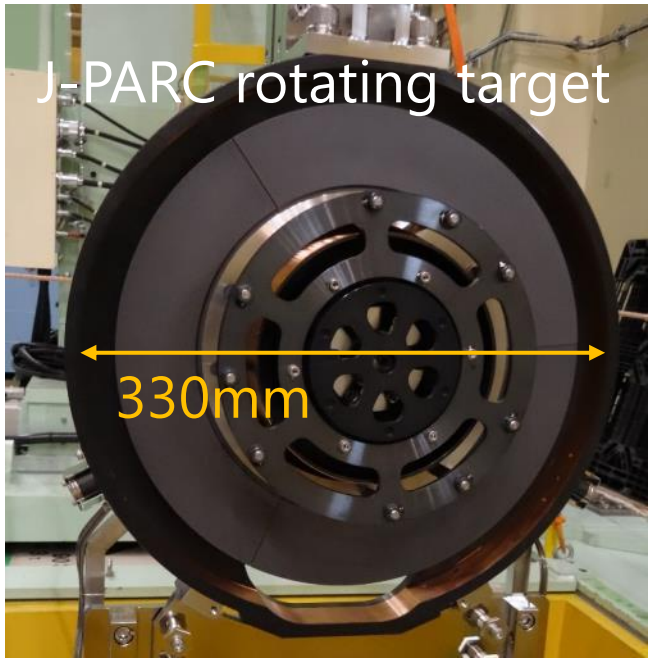
Rotating target 1/2

- 1MW proton beam causes 1dpa/year.
- Radioactivation of muon target = 5Sv/h, so replacement of muon target needs a lot of time and money.

Rotating target 2/2

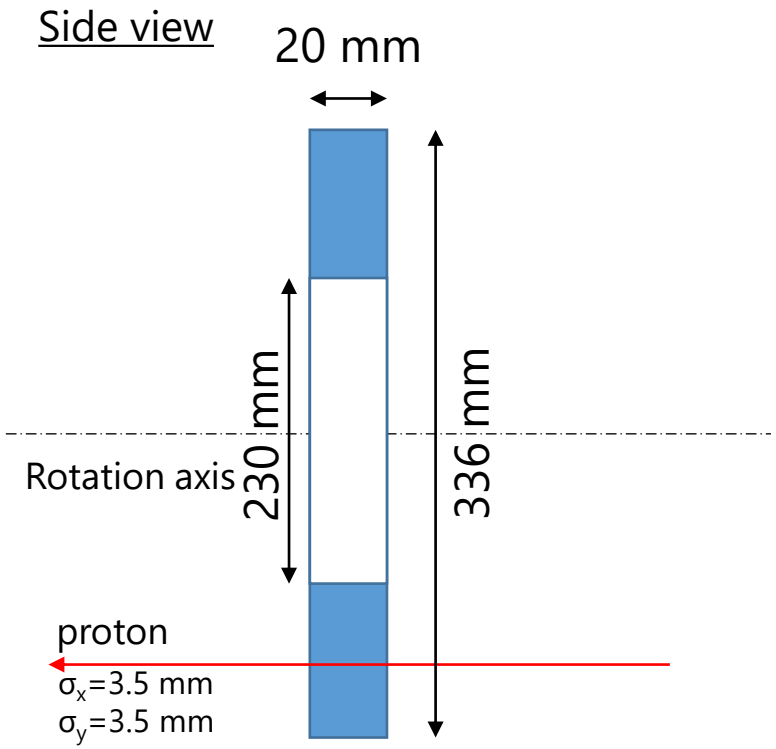
- Rotating target
  - Like a muon target @PSI
  - Disperse heat and radiation damage
  - Prolong target's lifetime
    - ✓ Lifetime of graphite = 30 years
    - ✓ Target lifetime is determined by the lifetime of the bearing (~10 years)
  - Graphite (IG-430U)
  - Thickness = 20mm
  - Rotating speed = 15rpm





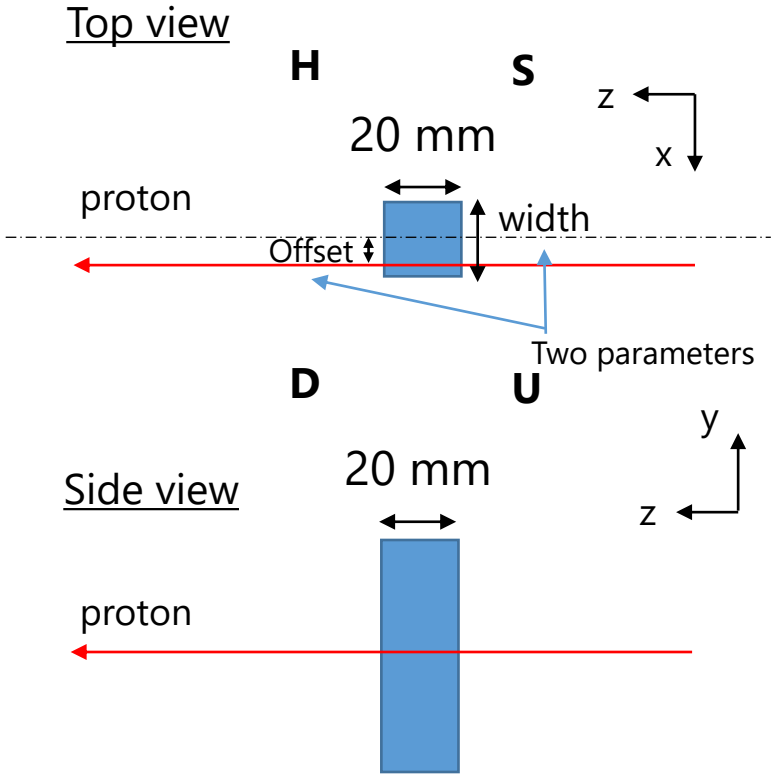
Shape of new target

Current rotating target



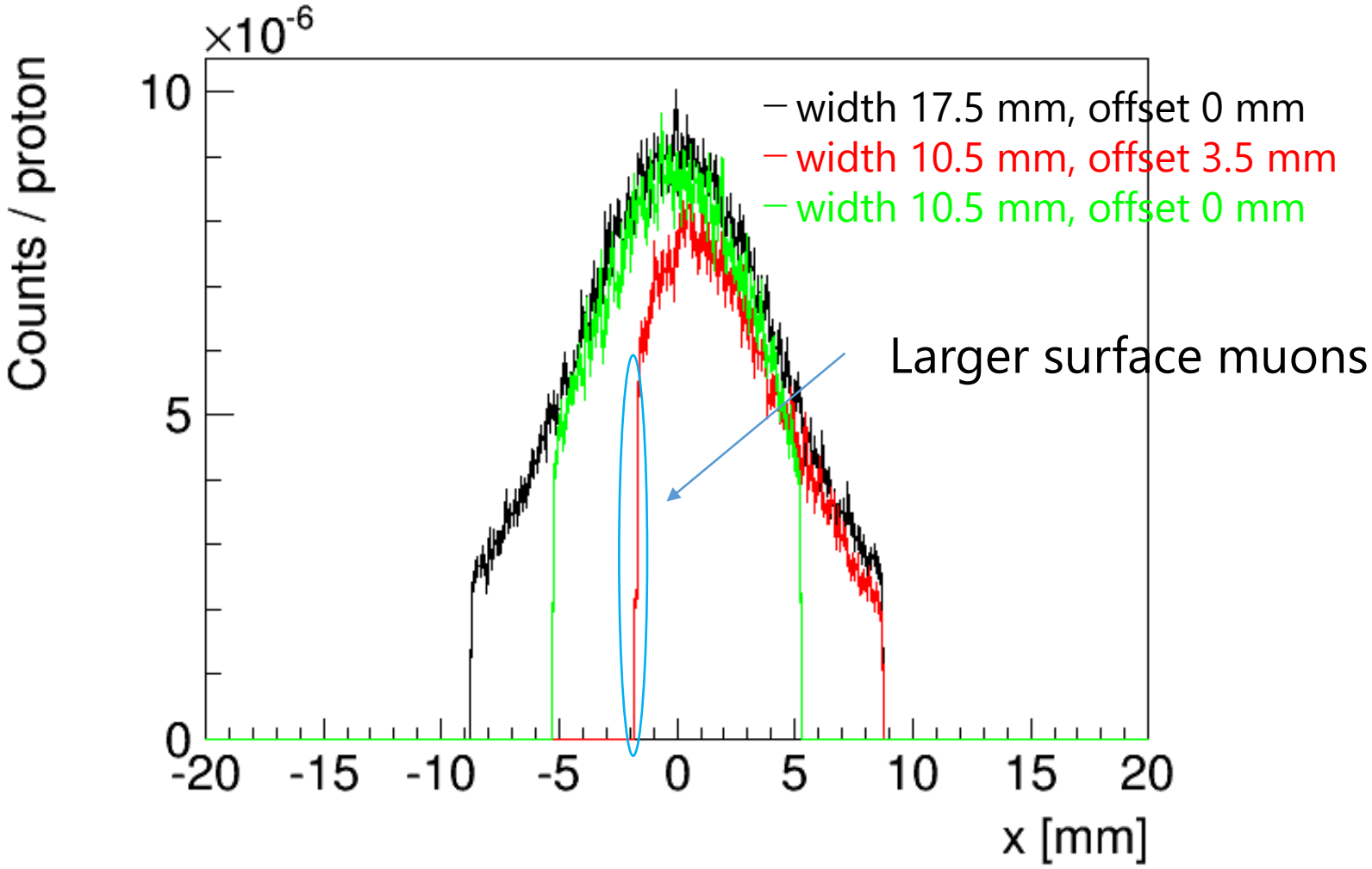
Rotation speed
15 rpm ~ 222 mm/s
To disperse heat & rad. damage

New idea

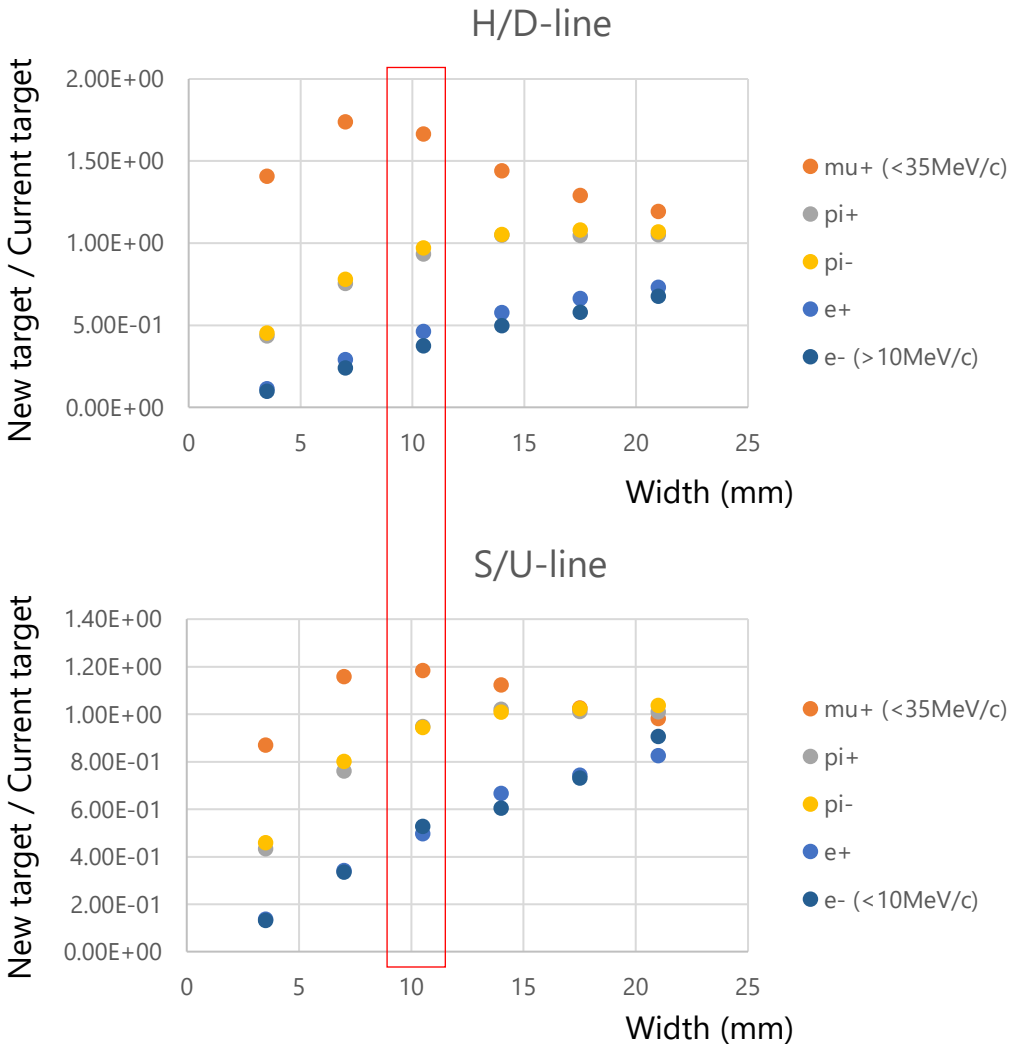


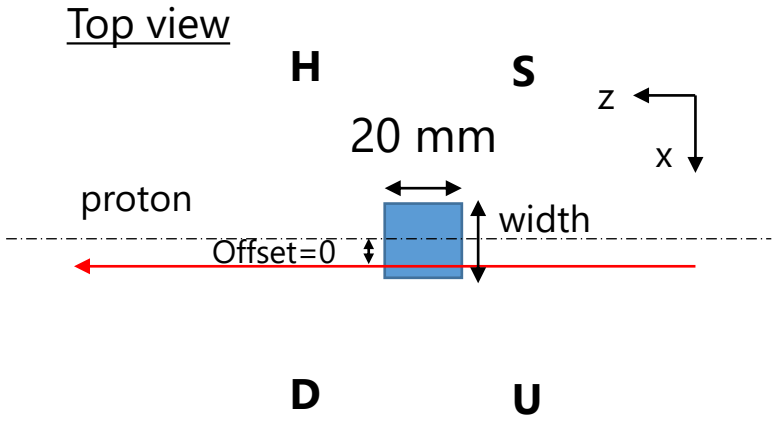
Q. How can we disperse damage?

π^+静止位置


×10^-6
10
5
0
Counts / proton
-20
-15
-10
-5
0
5
10
15
20
x [mm]
width 17.5 mm, offset 0 mm
width 10.5 mm, offset 3.5 mm
width 10.5 mm, offset 0 mm
Larger surface muons

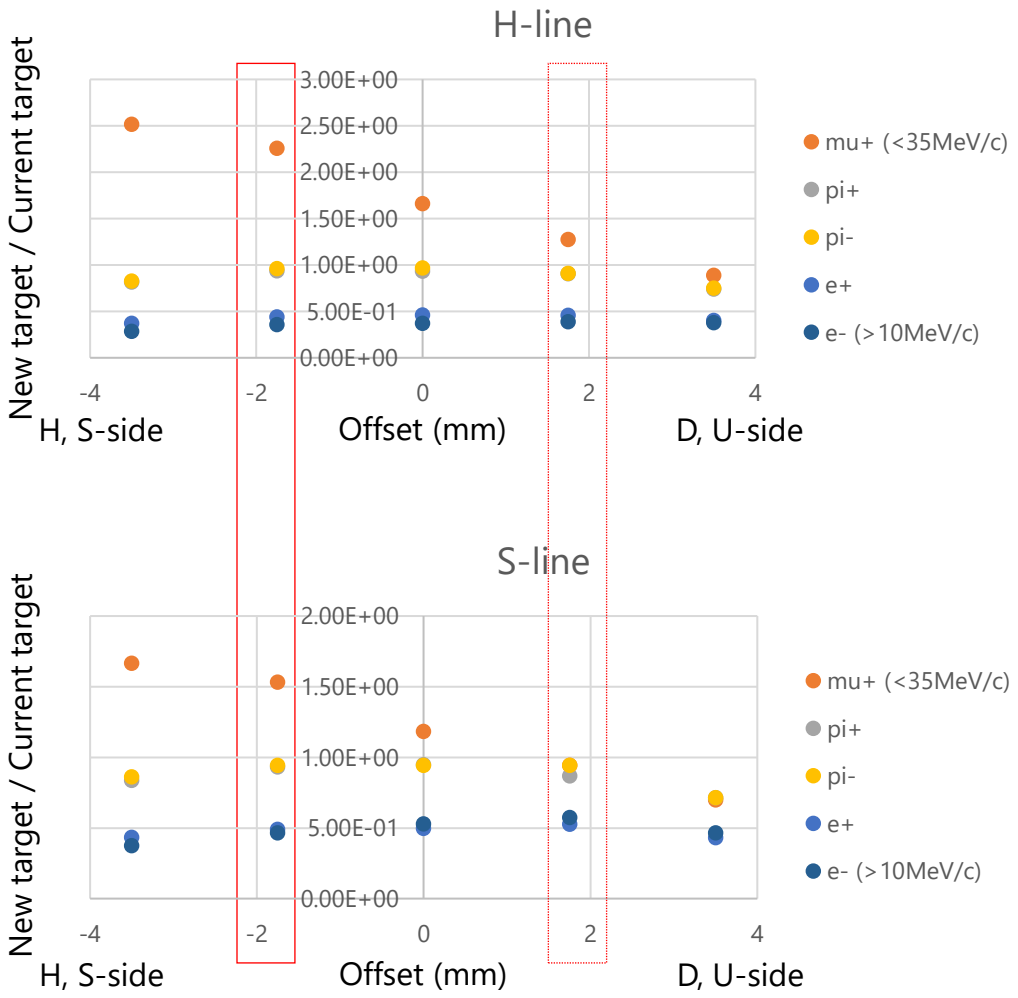
Width dependence

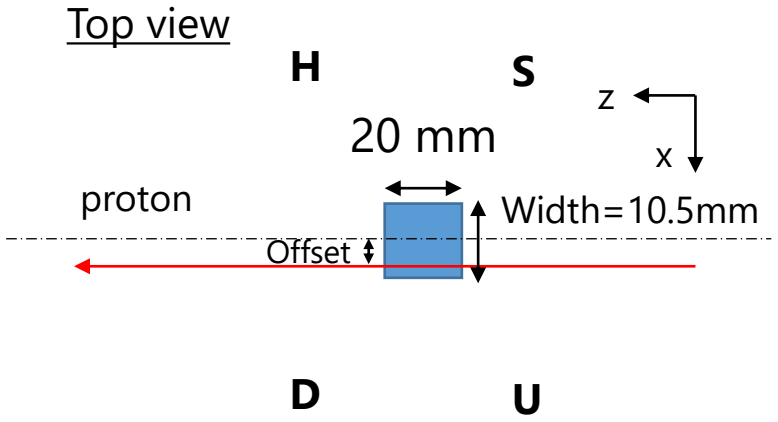




- Model: QGSP_INCLXX
- Intensity of decay muons (= pions) is also important for our facility
- Without offset, thickness of 10.5 mm seems best. Surface muons = 1.7x

Offset dependence





- Model: QGSP_INCLXX
- # of pions is not dependent strongly on offset.
- Offset = -1.75 mm, Surface muons are
  - ✓ H: 2.7x
  - ✓ D: 1.3x
  - ✓ S: 1.5x
  - ✓ U: 0.9x