



# Updates from the J-PARC experiment for the Muon $g-2$ /EDM Measurement

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on behalf of the J-PARC E34 Collaboration

# Muon g-2/EDM Experiments

The spin precession vector with respect to cyclotron motion in EM field

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

BNL/FNAL approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

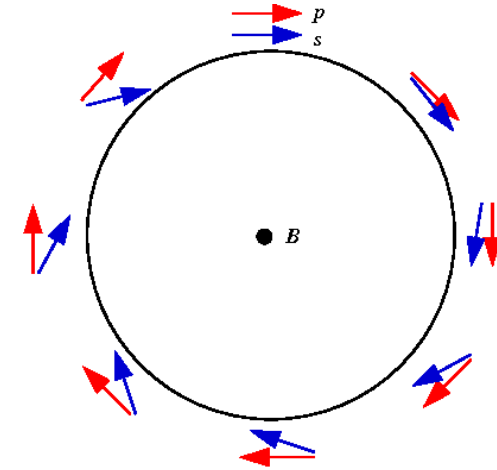
**Magic momentum of 3.094 GeV/c is used.**

J-PARC approach

$$\vec{E} = 0$$

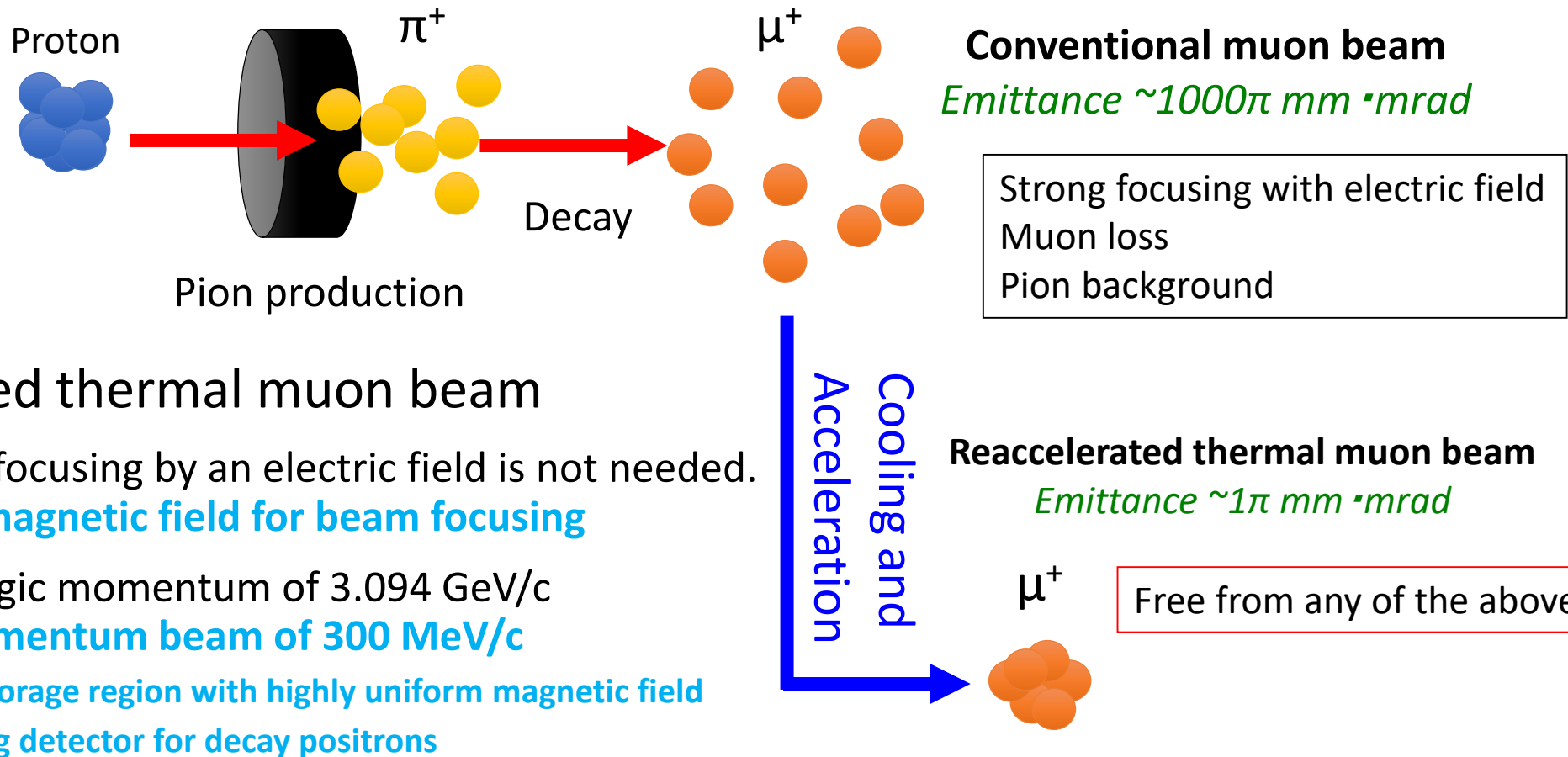
$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} (\vec{\beta} \times \vec{B}) \right]$$

**Reaccelerated thermal muon beam is a key of this method.**



Spin precession in cyclotron motion

# Reaccelerated Thermal Muon Beam



## Reaccelerated thermal muon beam

- Strong beam focusing by an electric field is not needed.  
→ **Gradient magnetic field for beam focusing**
- Free from magic momentum of 3.094 GeV/c  
→ **Lower momentum beam of 300 MeV/c**
  - **Compact storage region with highly uniform magnetic field**
  - **Full tracking detector for decay positrons**

# Comparison of Experiment Parameters

**Table 1.** Comparison of BNL-E821, FNAL-E989, and our experiment.

	BNL-E821	Fermilab-E989	Our experiment	J-PARC E34
Muon momentum		3.09 GeV/c	300 MeV/c	
Lorentz $\gamma$		29.3	3	
Polarization		100%	50%	
Storage field		$B = 1.45$ T	$B = 3.0$ T	
Focusing field		Electric quadrupole	Very weak magnetic	
Cyclotron period		149 ns	7.4 ns	
Spin precession period		4.37 $\mu$ s	2.11 $\mu$ s	
Number of detected $e^+$	$5.0 \times 10^9$	$1.6 \times 10^{11}$	$5.7 \times 10^{11}$	
Number of detected $e^-$	$3.6 \times 10^9$	—	—	
$a_\mu$ precision (stat.)	460 ppb	100 ppb	450 ppb	
(syst.)	280 ppb	100 ppb	<70 ppb	
EDM precision (stat.)	$0.2 \times 10^{-19} e \cdot \text{cm}$	—	$1.5 \times 10^{-21} e \cdot \text{cm}$	
(syst.)	$0.9 \times 10^{-19} e \cdot \text{cm}$	—	$0.36 \times 10^{-21} e \cdot \text{cm}$	

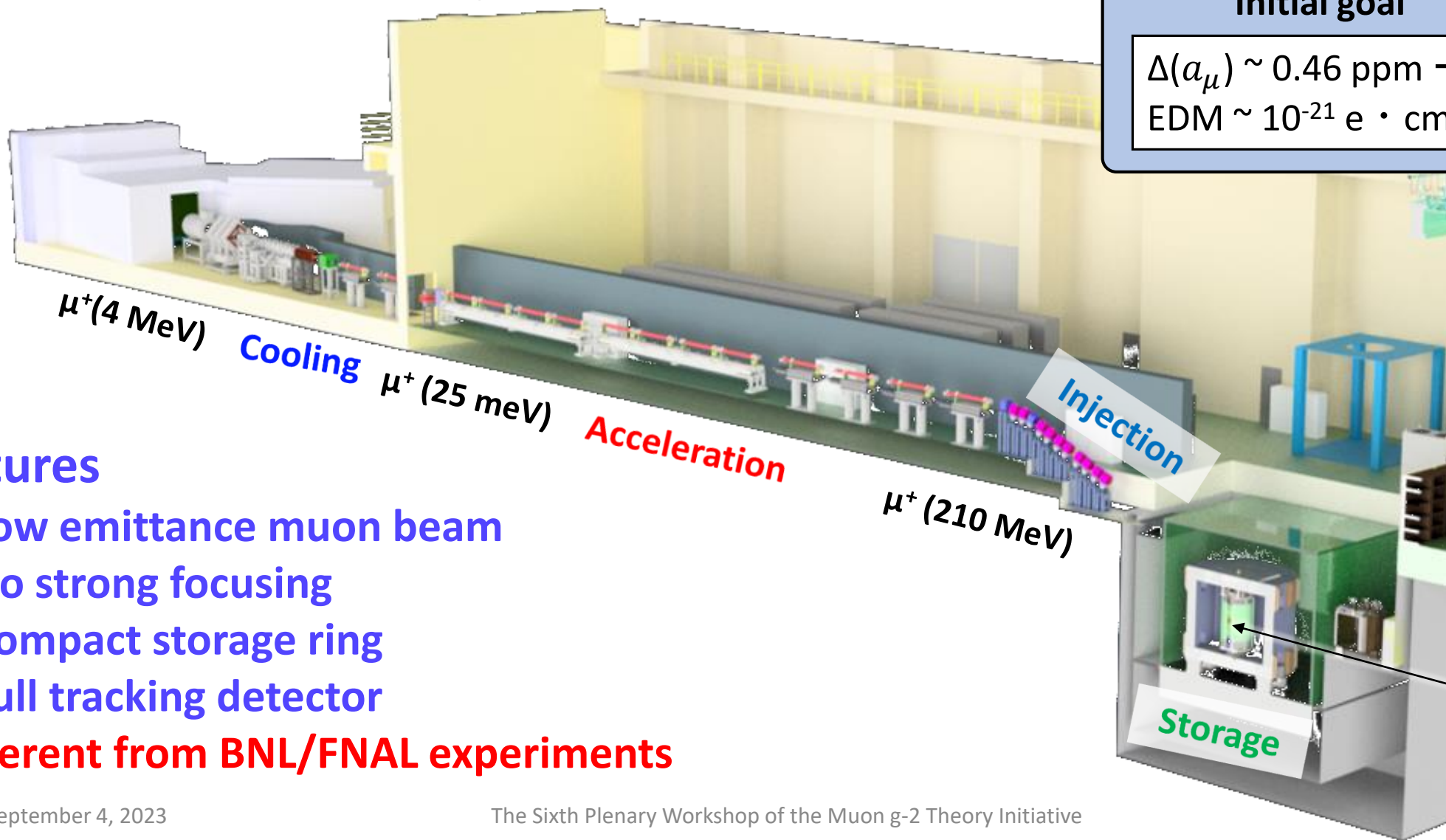
Radius of cyclotron  
motion: 7.1 m

Radius of cyclotron  
motion: 333 mm

[PTEP 2019 \(2019\), 053C02](#)

# J-PARC E34 Experiment

Initial goal	Final goal
$\Delta(a_\mu) \sim 0.46 \text{ ppm} \rightarrow 0.1 \text{ ppm}$ $\text{EDM} \sim 10^{-21} \text{ e} \cdot \text{cm}$	

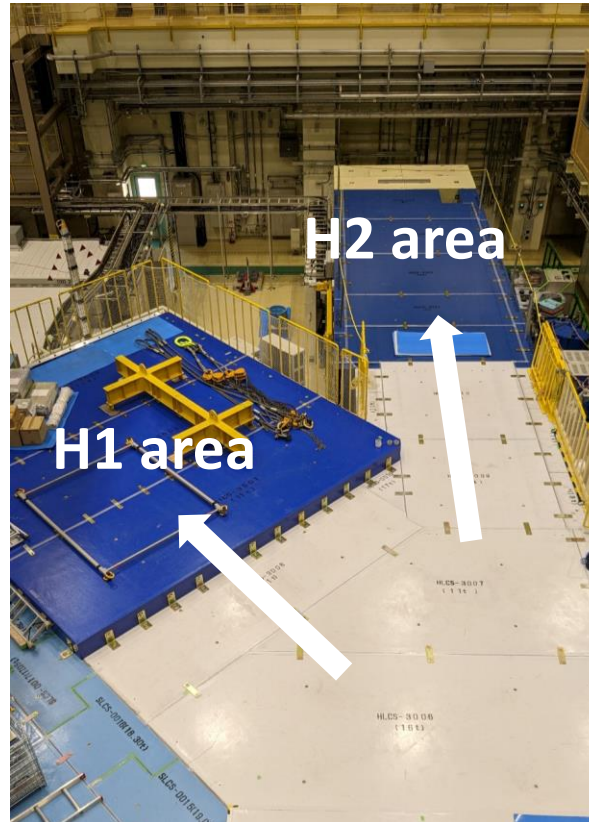


## Features

- Low emittance muon beam
- No strong focusing
- Compact storage ring
- Full tracking detector

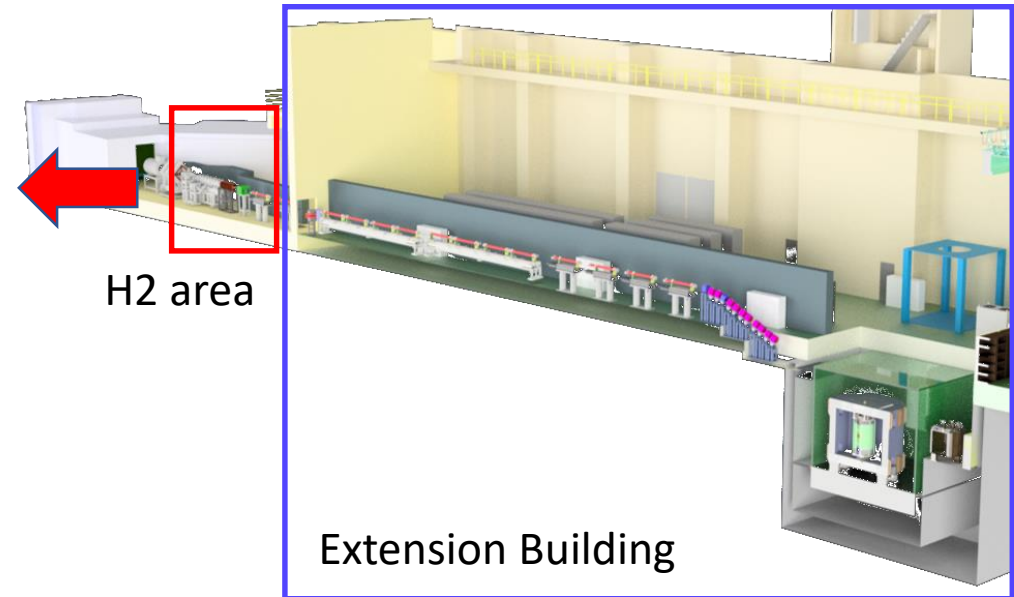
**Different from BNL/FNAL experiments**

# H-line Construction Status

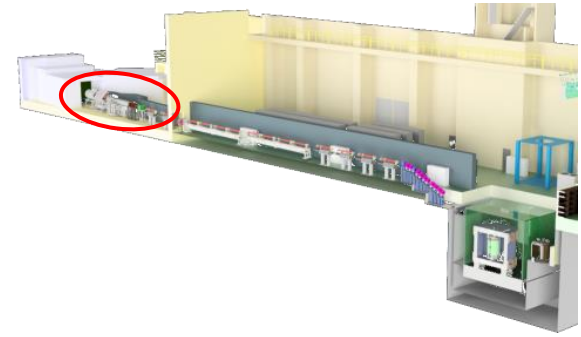


After the completion of H1 area construction, construction of H2 area has been conducted and it was recently completed.

The experiment will be performed at J-PARC MLF H-line, which is newly constructed.

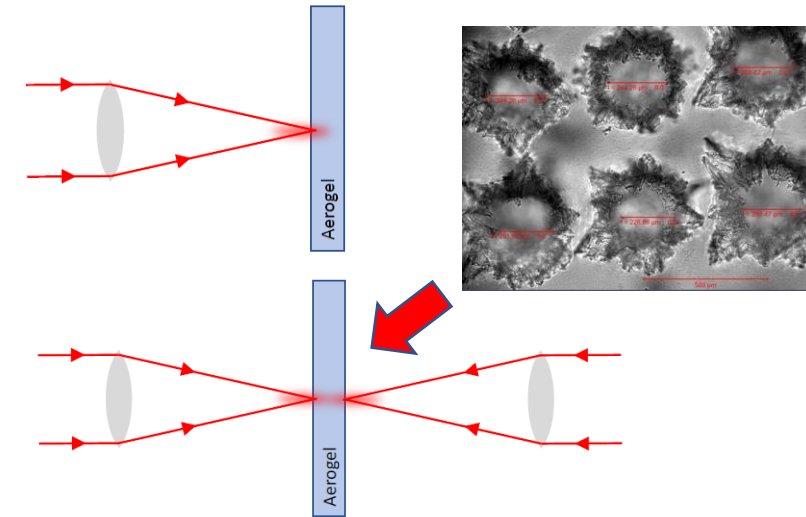
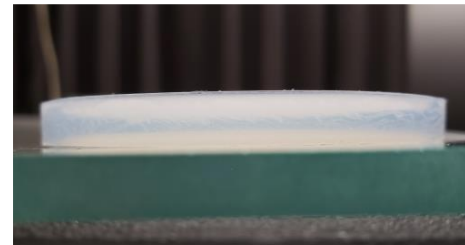
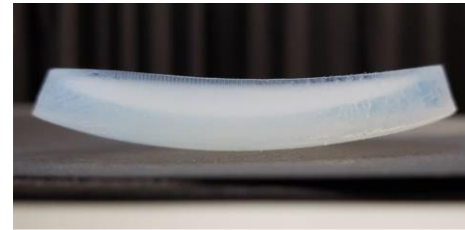
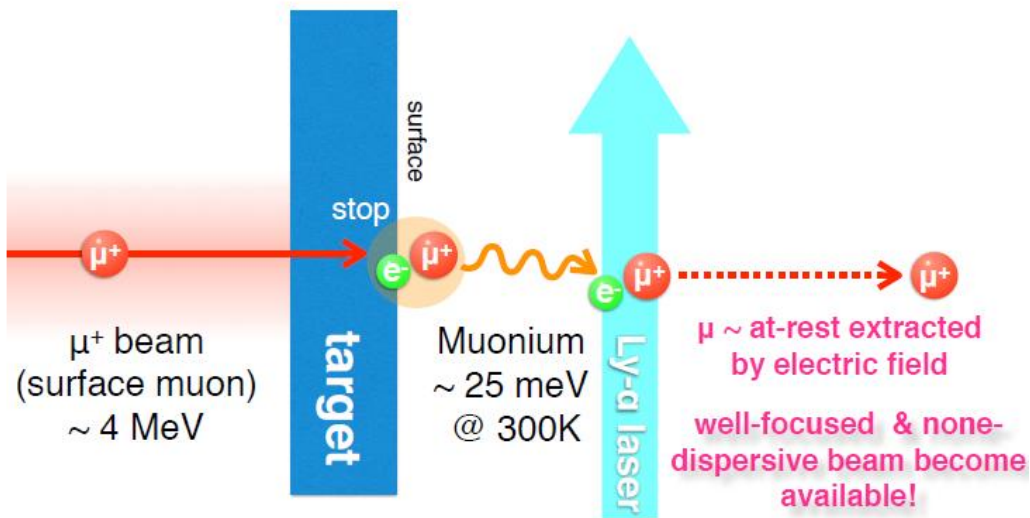


Engineering design of extension building is also ongoing.



# Thermal Muon Beam

- Surface muon beam from the H-line will be used as a source.
- Muon beam is stopped at an aerogel target, and muonium (bound state of  $e^-$  and  $\mu^+$ ) is produced.
  - Laser-ablated silica aerogel is used for muonium production target.
- An electron is stripped from a muonium by laser and thermal muon beam is produced.

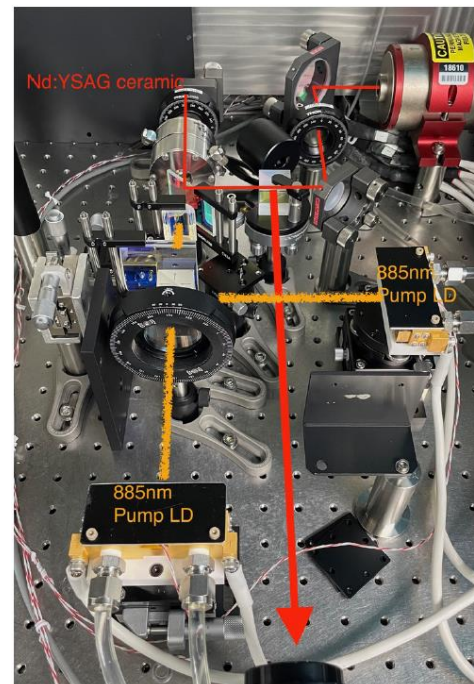
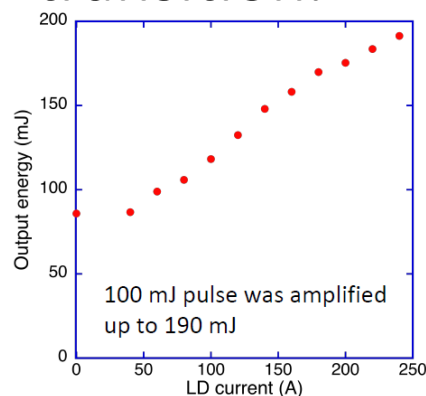


Double-sided laser ablation can reduce aerogel warping.

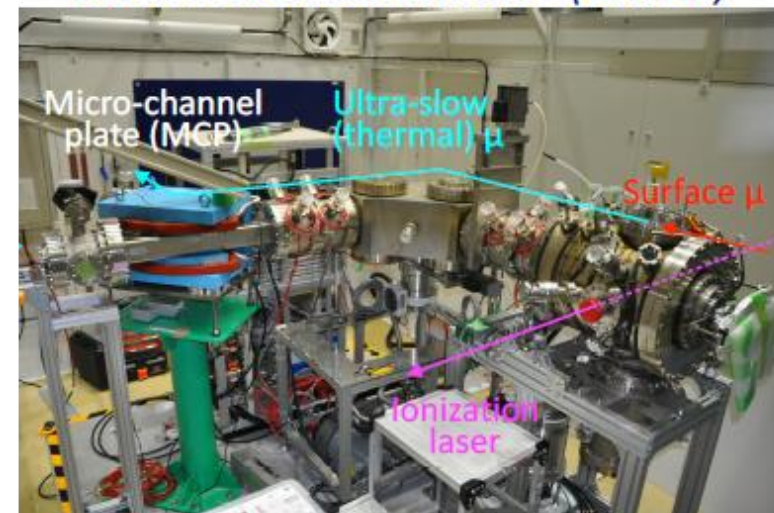
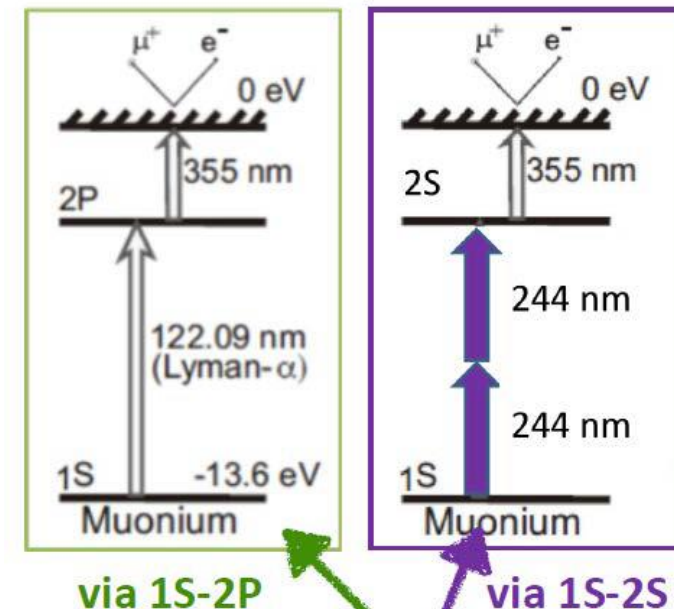
# Muonium Ionization

- In the original plan, an intense Lyman- $\alpha$  laser is used to ionize muonium via 1S-2P transition.

- New amplifier module improved pulse energy.



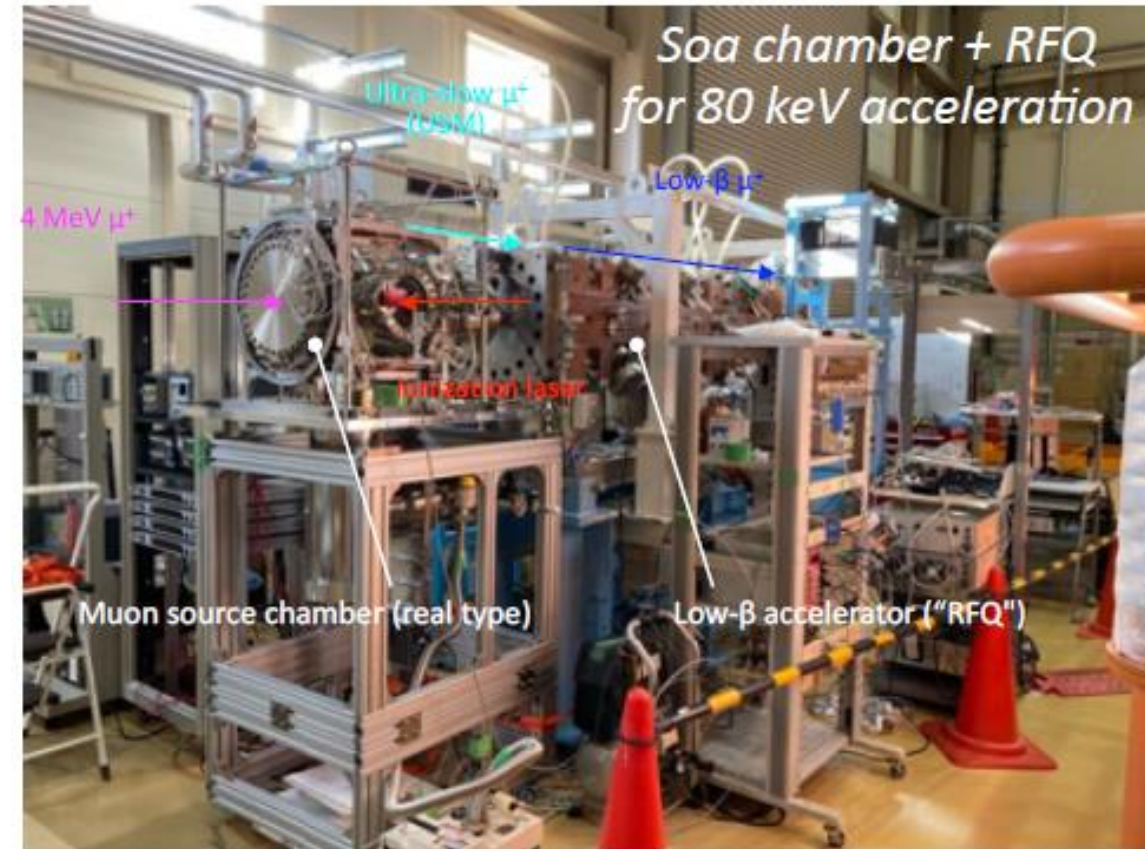
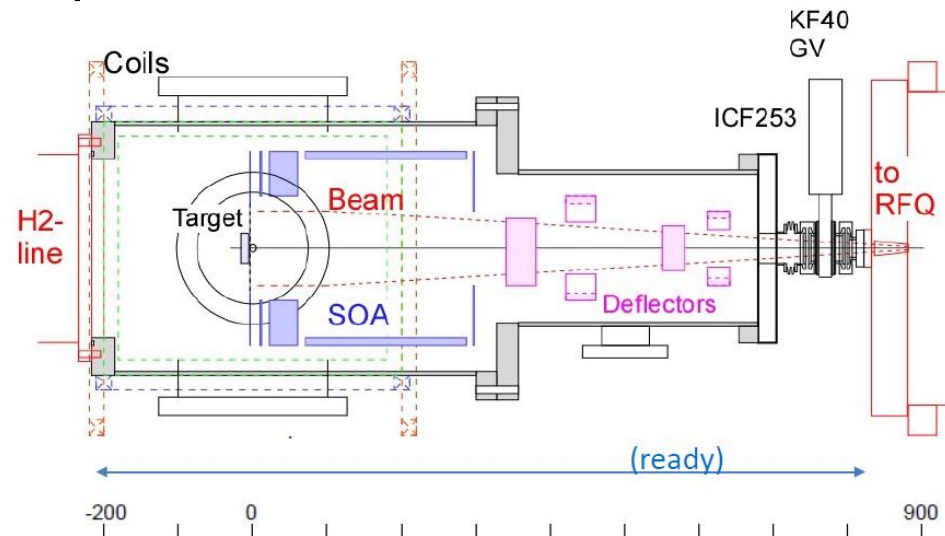
- As an alternative method, ionization scheme with 244 nm laser is being developed collaborating with the muonium 1S-2S spectroscopy measurement experiment.



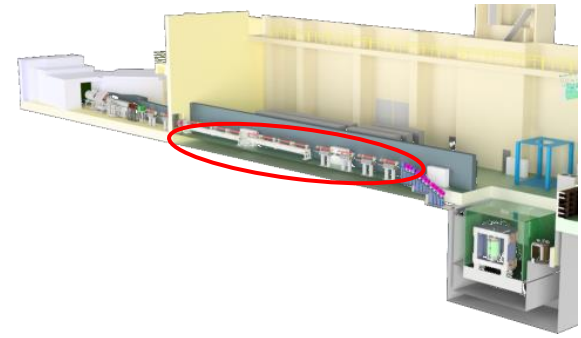
Slow muon beam line constructed for Mu 1S-2S experiment in S-line

# Muon Source Chamber

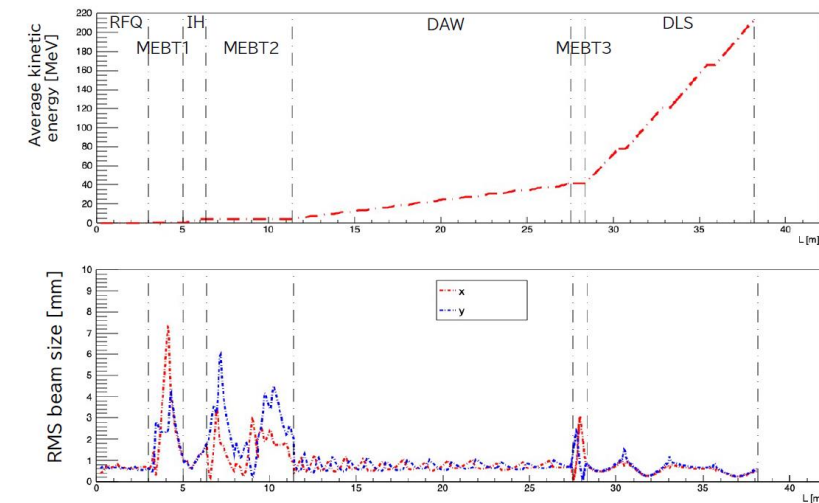
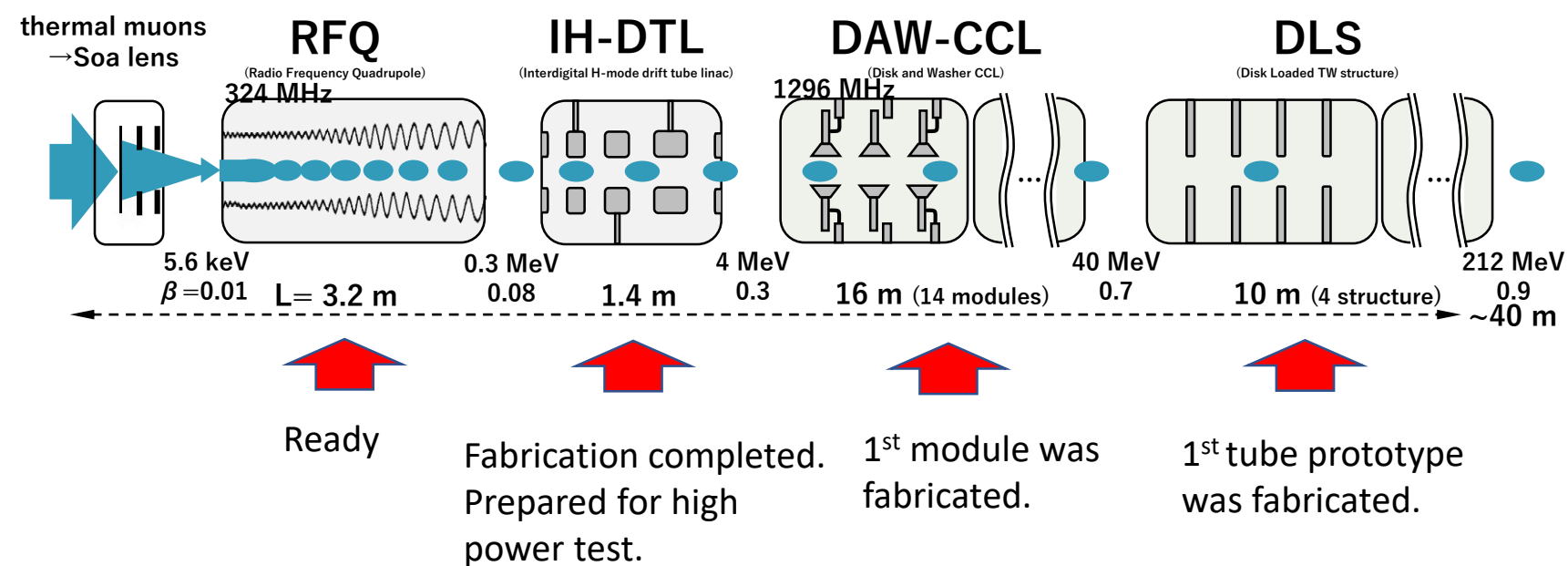
- Assembly of the muon source chamber to be used at the actual experiment was tested.
- Beam profile of ultra-slow muon from the chamber is being measured at J-PARC MLF.
- Acceleration test of ultra-slow muon with RFQ is planned.



# Muon Acceleration



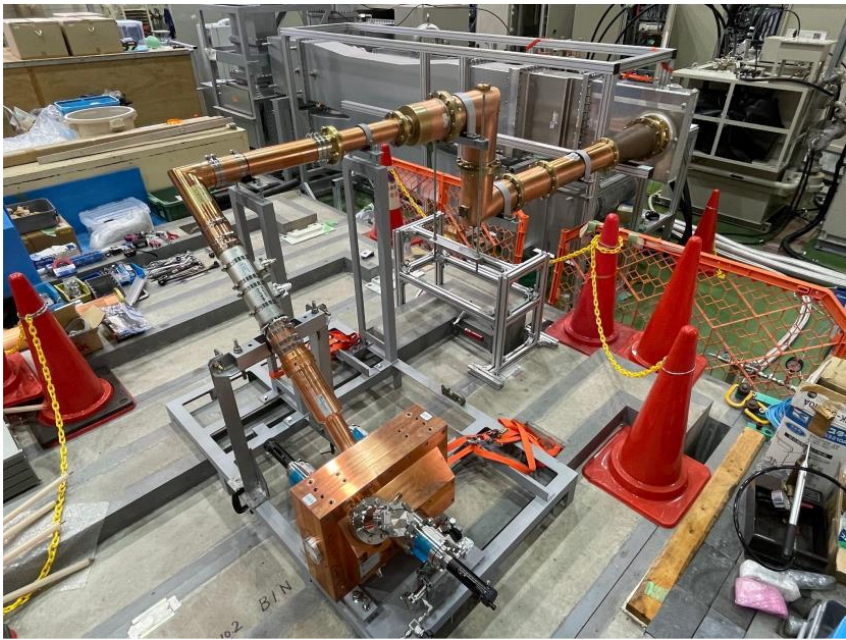
- Thermal muon beam is accelerated to  $p=300$  MeV/c.
- Different types of acceleration cavities are used optimized for each stage.



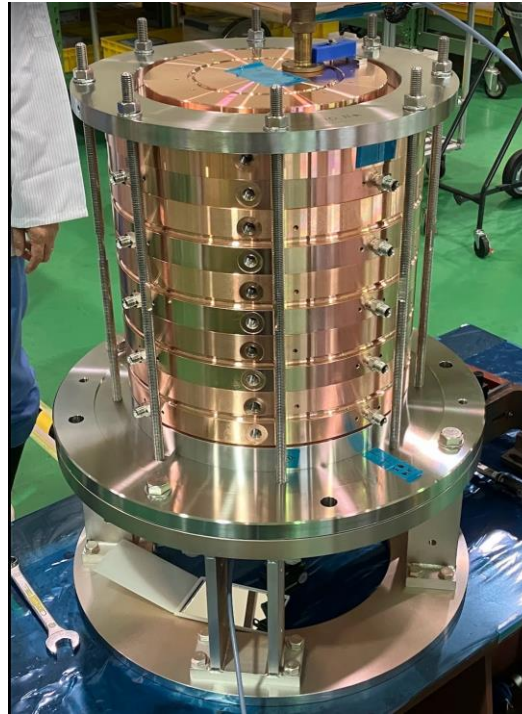
Beam parameter calculation

# Acceleration Cavities

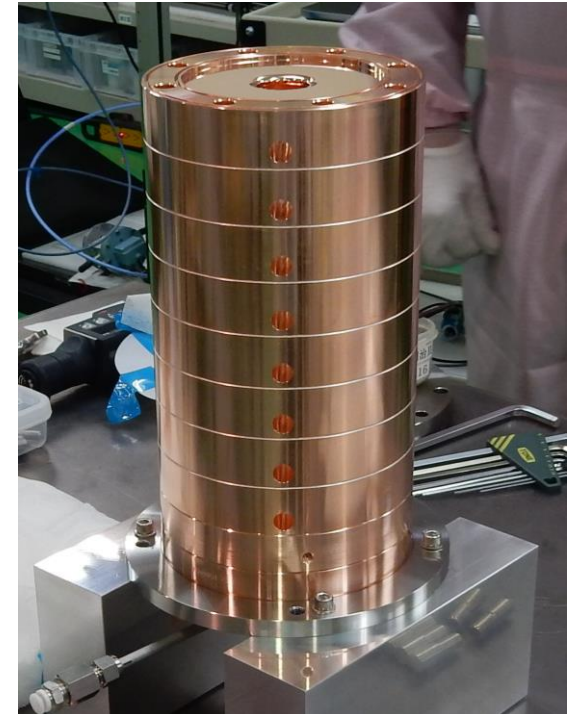
- Fabrication of acceleration cavities progresses well.



High power test of IH-DTL



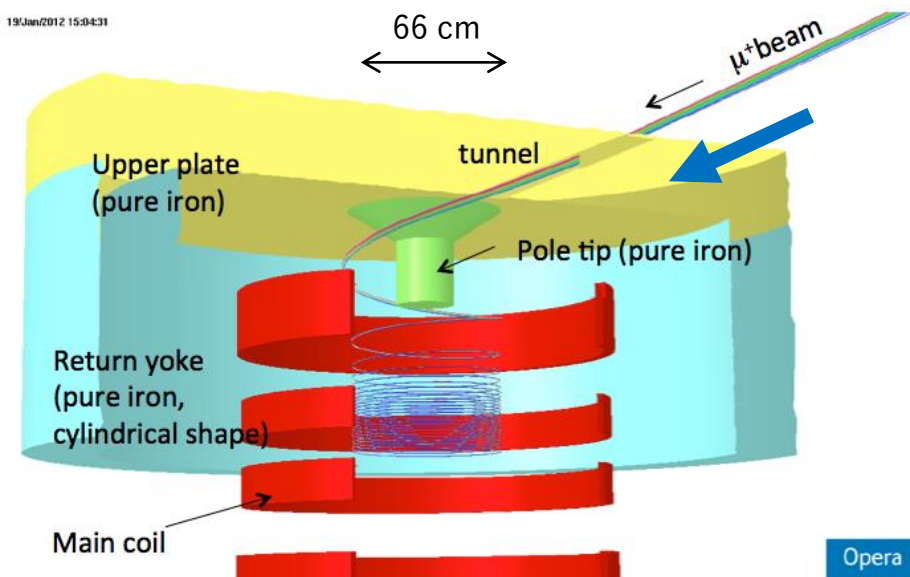
1<sup>st</sup> DAW module



1<sup>st</sup> DLS tube prototype

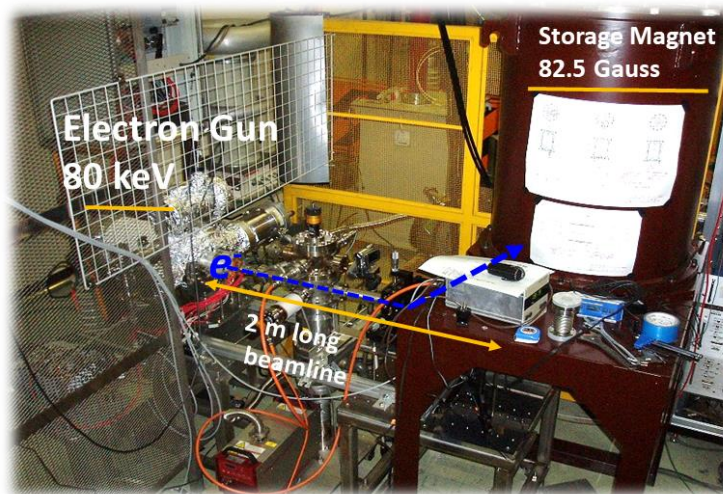
# 3D Spiral Injection

- To inject the 300 MeV/c muon beam into 66 cm-diameter storage ring, 3D spiral injection scheme is being developed.
- Prototypes of kicker were fabricated, and the injection scheme is validated using low momentum electron beam.



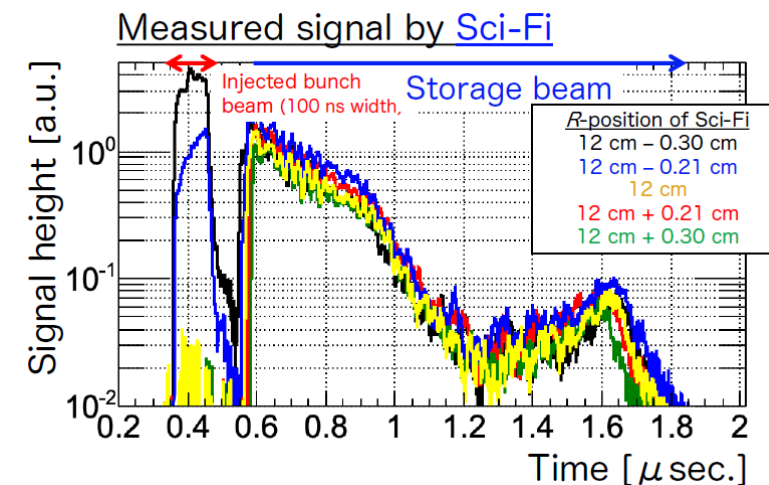
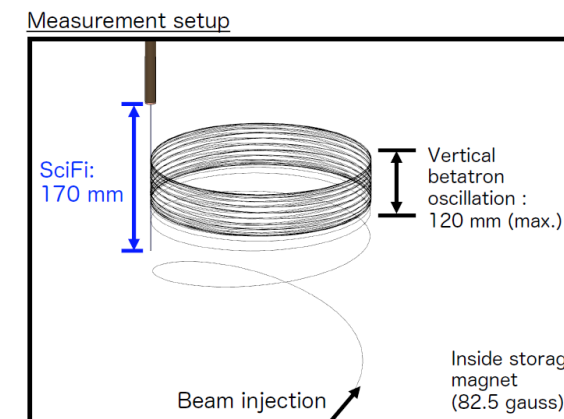
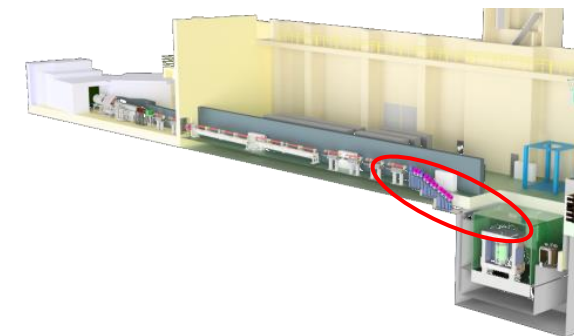
3D spiral Injection orbit

September 4, 2023



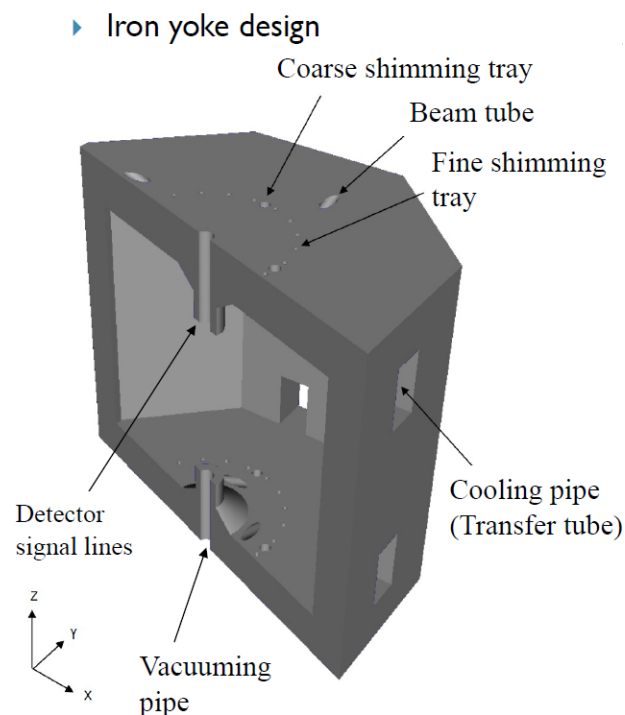
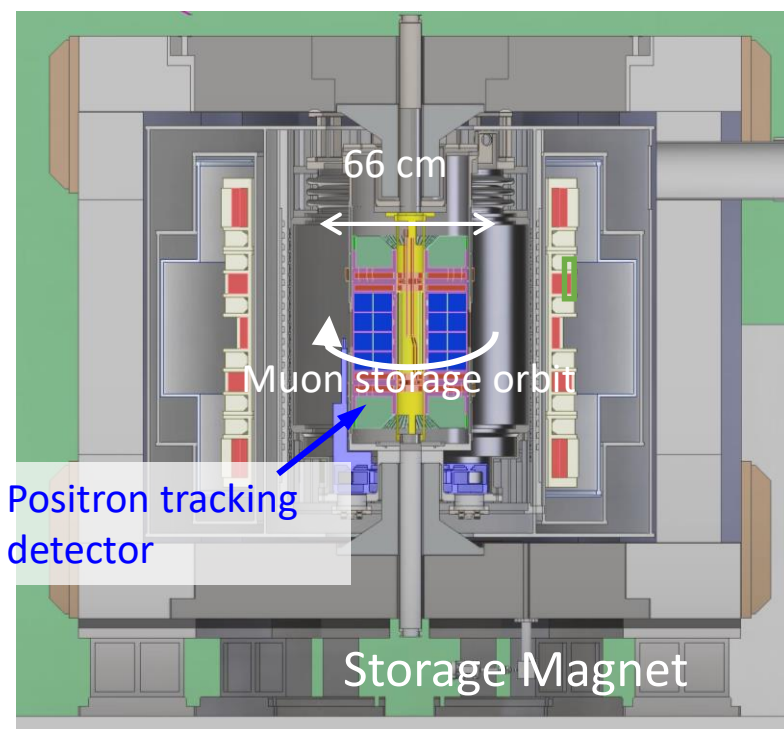
Beam storage was confirmed at the spiral beam injection test using low momentum electron.

The Sixth Plenary Workshop of the Muon g-2 Theory Initiative

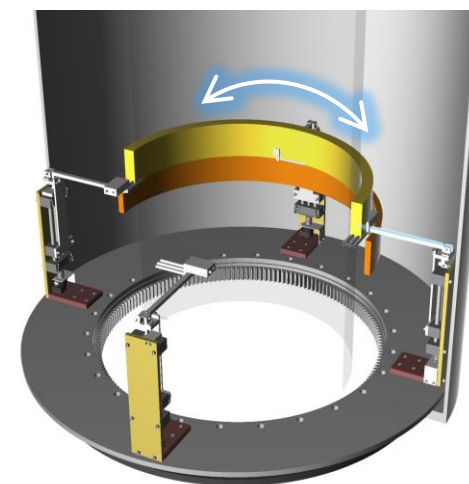


# Storage Magnet

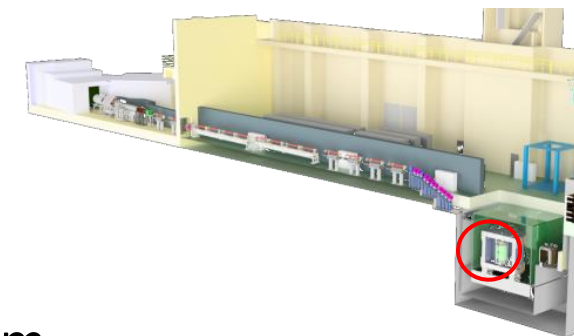
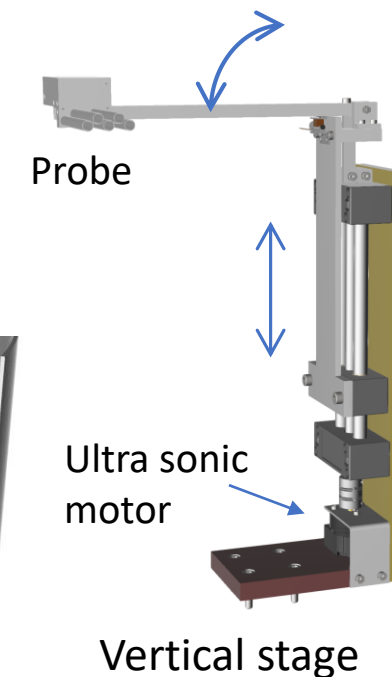
- 3 T MRI-type superconducting solenoid magnet is used to store a muon beam.
- Engineering design of the magnet is ongoing.
- Field monitoring system is also developed.



Azimuthal stage

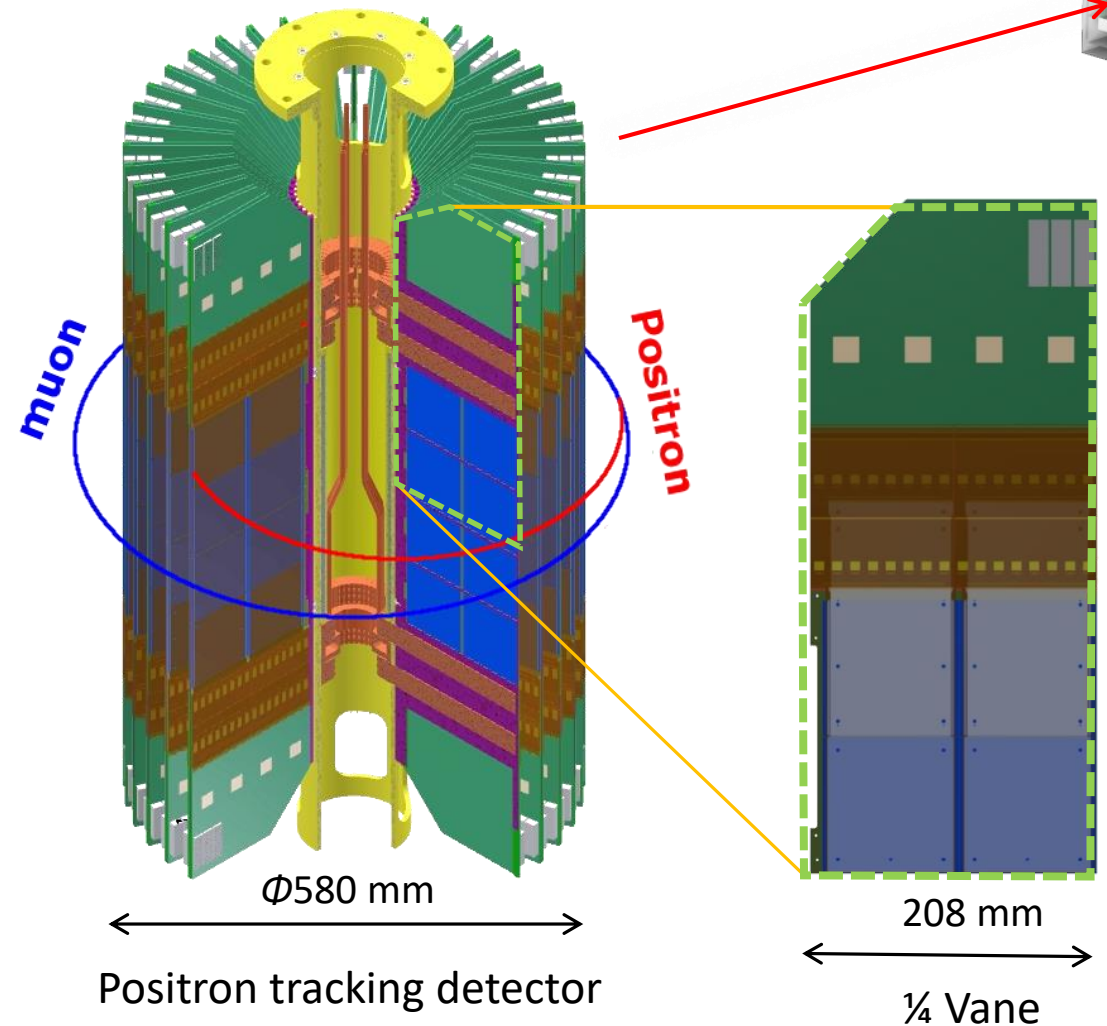


Moving stages for field monitoring



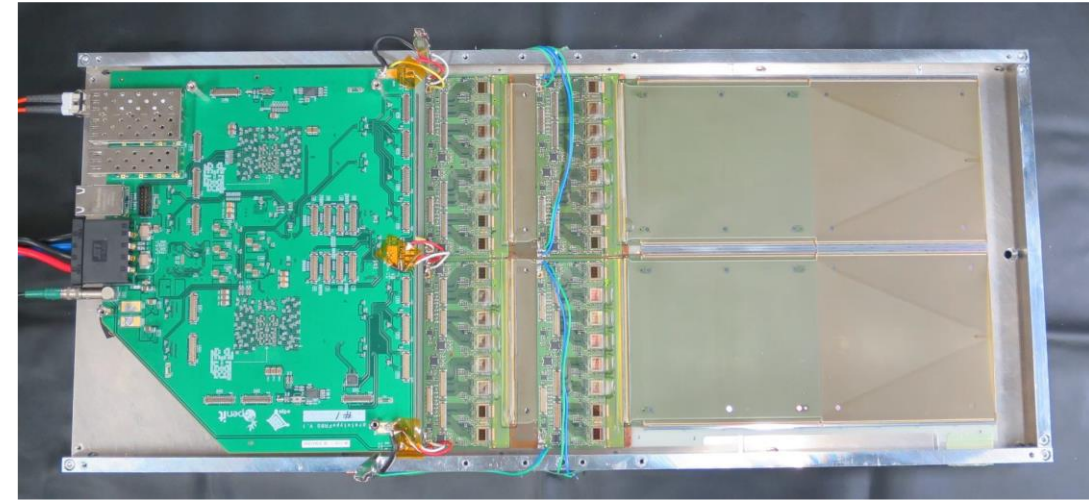
# Positron Tracking Detector

- Positrons from decay of stored muon beam are detected by the detector consisting of silicon strip sensors.
  - Positron tracks are reconstructed from hits in radially arranged detector modules (vanes).
  - Sensors with orthogonal strip direction in both sides of a vane
- The detector is required to operate in the highest muon decay rate of 6 tracks/ns.
  - 190  $\mu\text{m}$  pitch silicon strip sensor
  - 5 ns sampling rate in readout ASIC

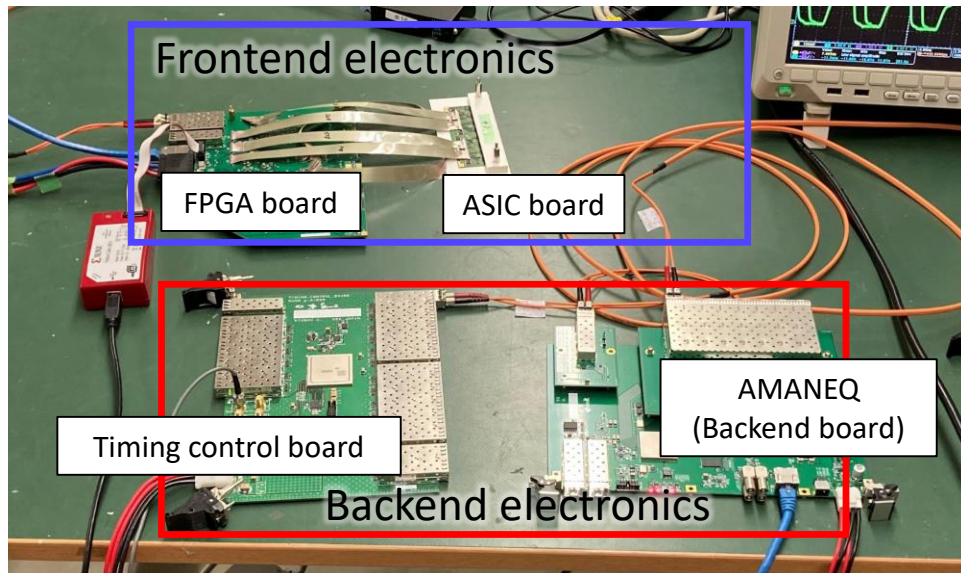


# Prototype Detector

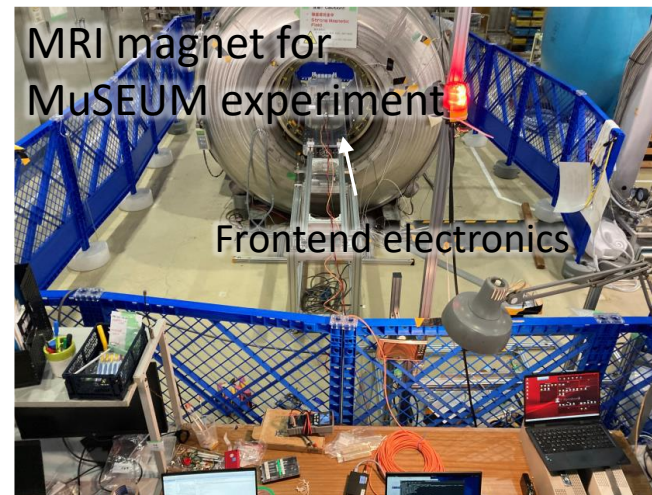
- Prototype of a  $\frac{1}{4}$  vane is assembled and electrical performance is being evaluated.
- Various operation tests are also performed using prototype electronics.



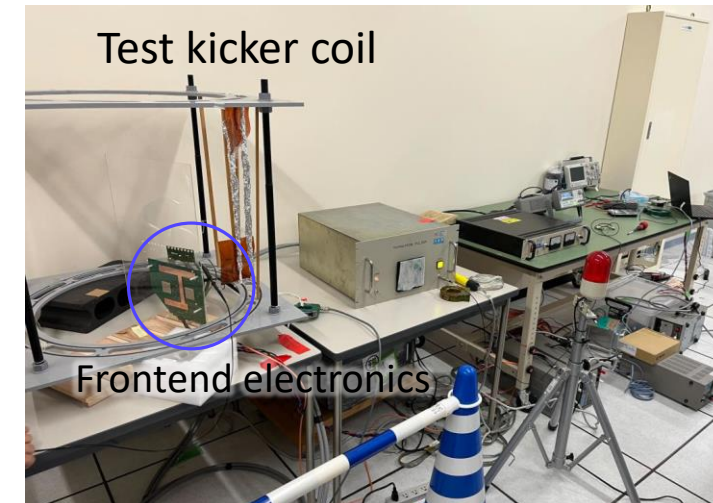
$\frac{1}{4}$  vane prototype



DAQ test between frontend and backend electronics



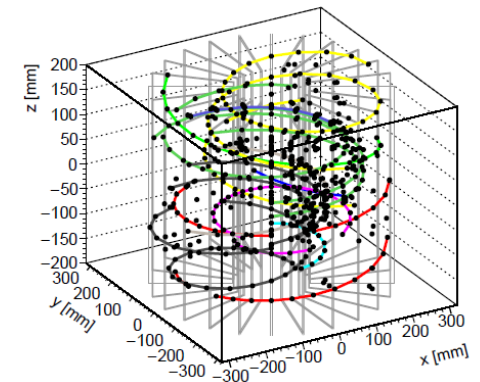
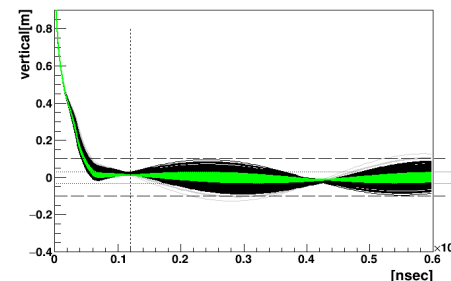
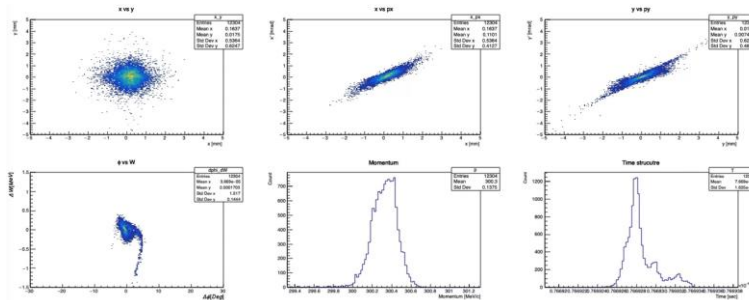
Operation test in strong magnetic field



Operation test in kicker magnetic field

# Software and Computing

- Software framework (g2esoft) was developed to manage detector simulation and track reconstruction.
- End-to-end simulation which starts from the muon beam from H-line to the detection in the storage magnet has been conducted.
- To support computing requirements at the actual experiment, Grid and CernVM File System (CVMFS) servers are set up.



# Experiment Status

Year	Events
2018	Stage-2 status granted by the KEK IPNS director
2019	Stage-2 status granted by the KEK IMSS director KEK-SAC endorsed the E34 for the near-term priority TDR summary paper publication
2023	KEK IPNS Progress Review

Year	Funding
2020	Grant-in-Aid “Specially Promoted Research” (2020-2025)
2022	Funding to prepare for construction
2023	Funding to prepare for construction

We started preparation for the funding request to start construction for FY2024.



26<sup>th</sup> Collaboration Meeting in June 2023  
@J-PARC

# Schedule

- Construction of experimental apparatus is ongoing aiming at the start of the experiment in 2028 JFY.

JFY	2022	2023	2024	2025	2026	2027	2028 and beyond
KEK Budget							
Surface muon	✓ Beam at H1 area			★ Beam at H2 area			
Bldg. and facility			★ Final design			★ Completion	
Muon source		★ Ionization test at S2		★ Ionization test at H2			
LINAC		★ 80keV acceleration@S2		★ 4.3 MeV@ H2		★ fabrication complete	★ 210 MeV
Injection and storage		★ Completion of electron injection test					★ muon injection
Storage magnet				★ B-field probe ready		★ Install	★ Shimming done
Detector		★ Quater vane prototype		★ Mass production ready			★ Installation
DAQ and computing		★ grid service open	★ common computing resource usage start	★ small DAQ system operation test		★ Ready	
Analysis				★ Tracking software ready		★ Analysis software ready	

Commissioning  
Data taking

# Summary

- In the J-PARC E34 experiment, measurement of muon  $g-2$  and EDM is planned with a method different from BNL/FNAL experiments.
- Construction of the beam line was completed up to H2 area.
- Preparation of the experiment is ongoing aiming at the start of the data taking in 2028 JFY.

# Backup

# Muon Facility at J-PARC

## S-line

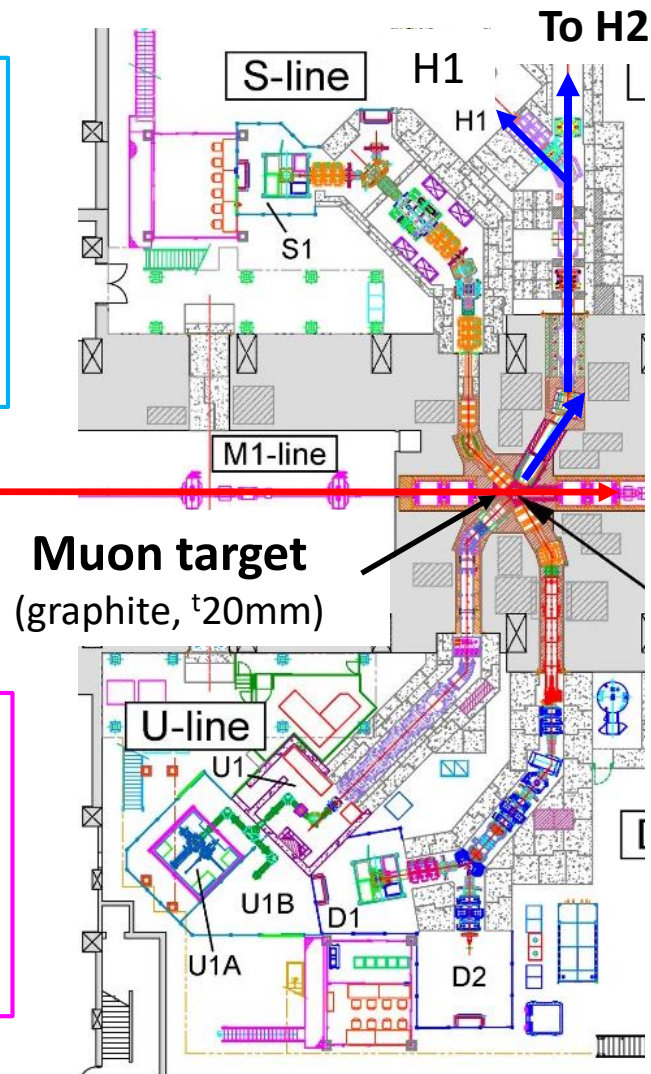
- surface  $\mu^+$
- dedicated to  $\mu$ SR
- S1 area is available
- S2 is under construction
- S3/S4 are planned

3 GeV proton from RCS

$2 \times 10^{15}$  /s @1MW

## U-line

- ultra slow  $\mu^+$
- U1A for nm- $\mu$ SR
- U1B for  $\mu$  microscopy
- under commissioning



## H-line

- surface  $\mu^+$  ( $>10^8 \mu^+/s$ ), decay  $\mu^+/\mu^-$ ,  $e^-$
- for high intensity & long beamtime experiments
- H1 for DeeMe & MuSEUM
- H2 for  **$g-2$ /EDM** & transmission muon microscopy
- **under construction**

## D-line

- decay  $\mu^+/\mu^-$ , surface  $\mu^+$
- D1 area for  $\mu$ SR
- D2 for variety of science

# Statistics Estimation

- The expected initial muon rate at 1 MW proton beam is  $\sim 2 \times 10^9/\text{sec}$ .
- Cumulative efficiency from the initial muon production target to the detected positrons is  $1.3 \times 10^{-5}$ .
- Then, the total number of the detected positrons at  $2 \times 10^7$  sec run ( $\sim 230$  days) is  $5.7 \times 10^{11}$ .

**Table 4.** Breakdown of estimated efficiency.

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	$e^+$ energy window	0.12
IH transmission	0.99	Detector acceptance of $e^+$	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

**Table 5.** Summary of statistics and uncertainties.

	Estimation
Total number of muons in the storage magnet	$5.2 \times 10^{12}$
Total number of reconstructed $e^+$ in the energy window [200, 275 MeV]	$5.7 \times 10^{11}$
Effective analyzing power	0.42
Statistical uncertainty on $\omega_a$ [ppb]	450
Uncertainties on $a_\mu$ [ppb]	450 (stat.) < 70 (syst.)
Uncertainties on EDM [ $10^{-21}$ e·cm]	1.5 (stat.) 0.36 (syst.)

[PTEP 2019 \(2019\), 053C02](#)

# Systematic Uncertainties of $a_\mu$

- Major sources of systematic uncertainties of  $\omega_a$  and  $\omega_p$  which consist  $a_\mu$  are estimated to be the following.

**Table 6.** Estimated systematic uncertainties on  $a_\mu$ .

Anomalous spin precession ( $\omega_a$ )		Magnetic field ( $\omega_p$ )	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Differential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

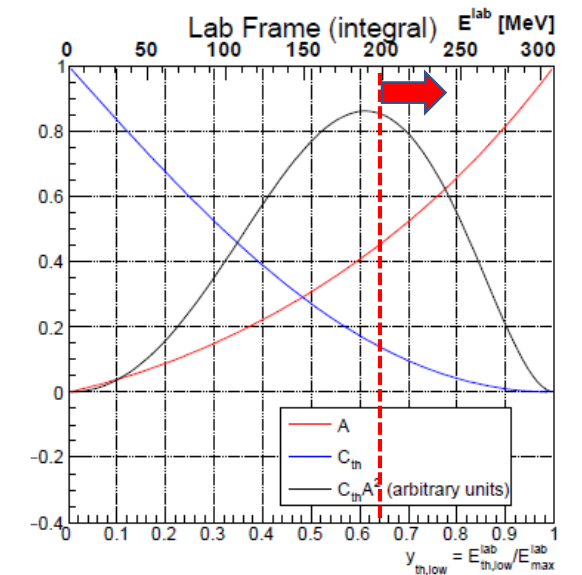
[PTEP 2019 \(2019\), 053C02](#)

# Statistical Uncertainty of $a_\mu$

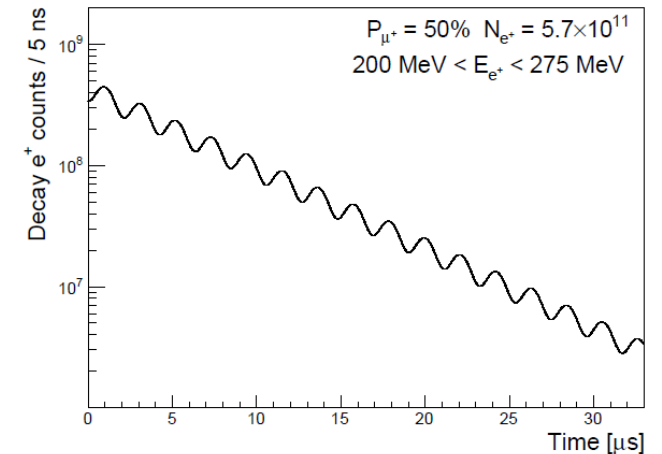
- The momentum range of the decay positions is determined to be [200,275] MeV/c from the detector acceptance and to maximize the analyzing power.
- The statistical uncertainty on  $a_\mu$  (or  $\omega_a$ , to be precise) is estimated to be 0.45 ppm from the following five-parameter-function fit to a toy wiggle plot

$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \cos(\omega_a t + \varphi)].$$

- The toy MC fit result is consistent with the analytical estimation of the statistical uncertainty on  $\omega_a$  of  $\Delta\omega_a = \frac{\sqrt{2}}{\gamma\tau A\sqrt{N}}$  where,  $N$  is the total number of detected positrons.



Analyzing power as a function of the momentum threshold



Toy simulation of a time spectrum of the number of decay positrons