KYUSHU UNIVERSITY

Status of Muon g-2/EDM Experiment at J-PARC

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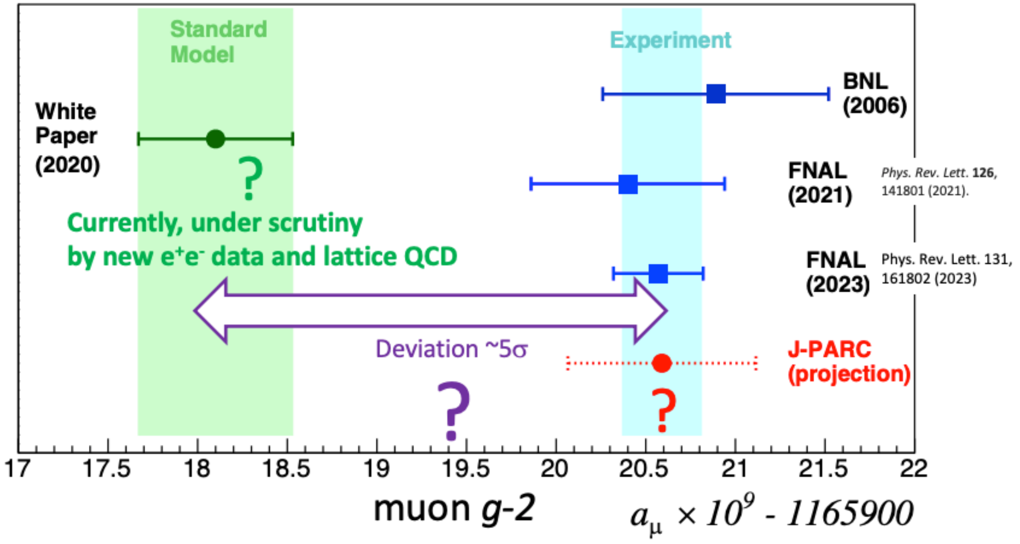
on behalf of the J-PARC E34 Collaboration

Muon g-2 and EDM

- Muon anomalous magnetic moment (g-2)
  - The latest result was published from FNAL E989 in last year and it was consistent with the previous result and the BNL experiment.
    - Phys. Rev. Lett. **131**, 161802 (2023)
    - Final result of FNAL E989 is expected in 2025.
  - The difference between the combined experimental value and the SM value exceed 5σ.
    - Muon g-2 theory initiative workshop was held at KEK (link) and it was agreed to updated the SM value in 2025.
- Muon electric dipole moment (EDM)
  - Existence of EDM for elementary particles indicates CP violation.
  - The experimental bound: $|d_\mu| < 1.8 \times 10^{-19}$ e・cm
    - BNL E821：PRD 80, 052008 (2009)

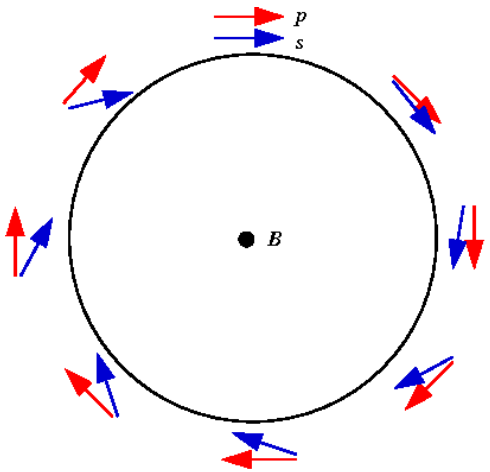


The Seventh Plenary Workshop of the Muon g-2 Theory Initiative at KEK

Experimental Approaches

Spin precession vector with respect to cyclotron motion in EM field

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



Spin precession in cyclotron motion

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

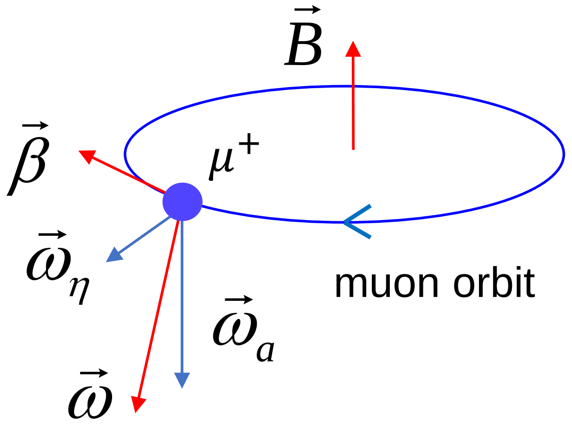
$$\vec{E} = 0$$

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

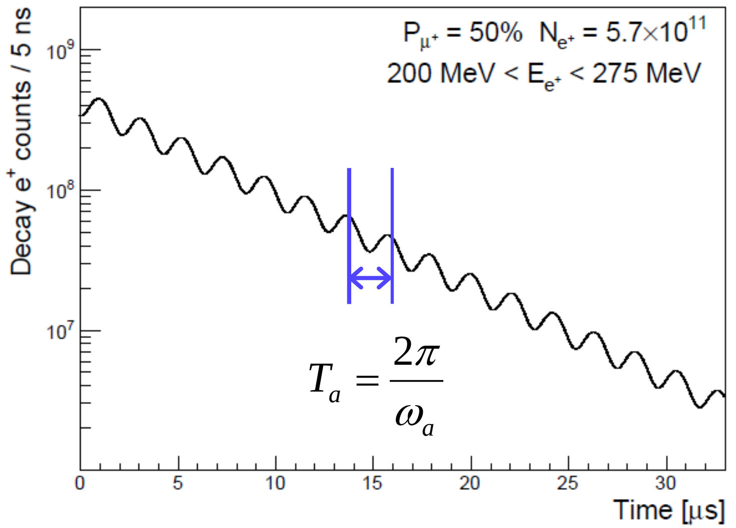
Reaccelerated thermal muon beam is a key of this method.

Measurement Principle

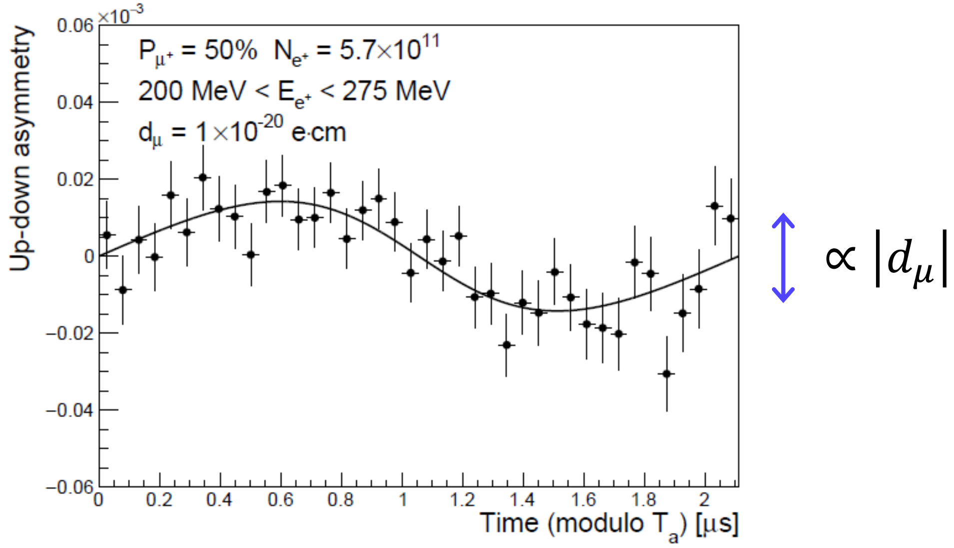
- Once electric field contribution is eliminated, g-2 and EDM can be obtained from the time spectrum of the number positrons from muon decay.



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

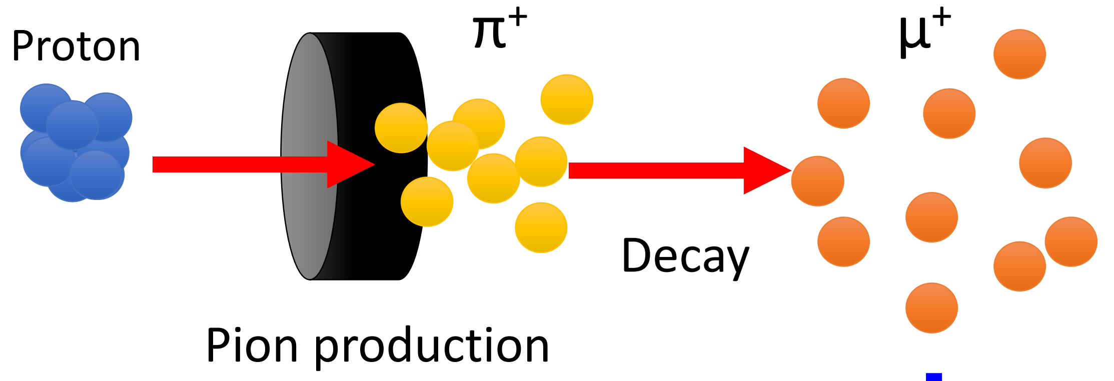


Time spectrum of the number of positrons from muon decay



Up-down asymmetry of positrons from muon decay

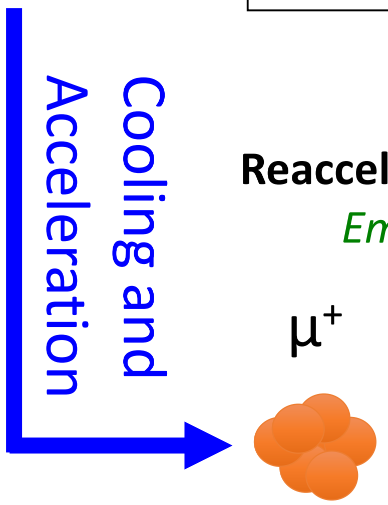
Reaccelerated Thermal Muon Beam



Conventional muon beam

Emittance ~1000π mm ·mrad

Strong focusing with electric field
Muon loss
Pion background



Reaccelerated thermal muon beam

Emittance ~1π mm ·mrad

Free from any of the above

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
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	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 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	–	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm

J-PARC E34 (Our experiment)

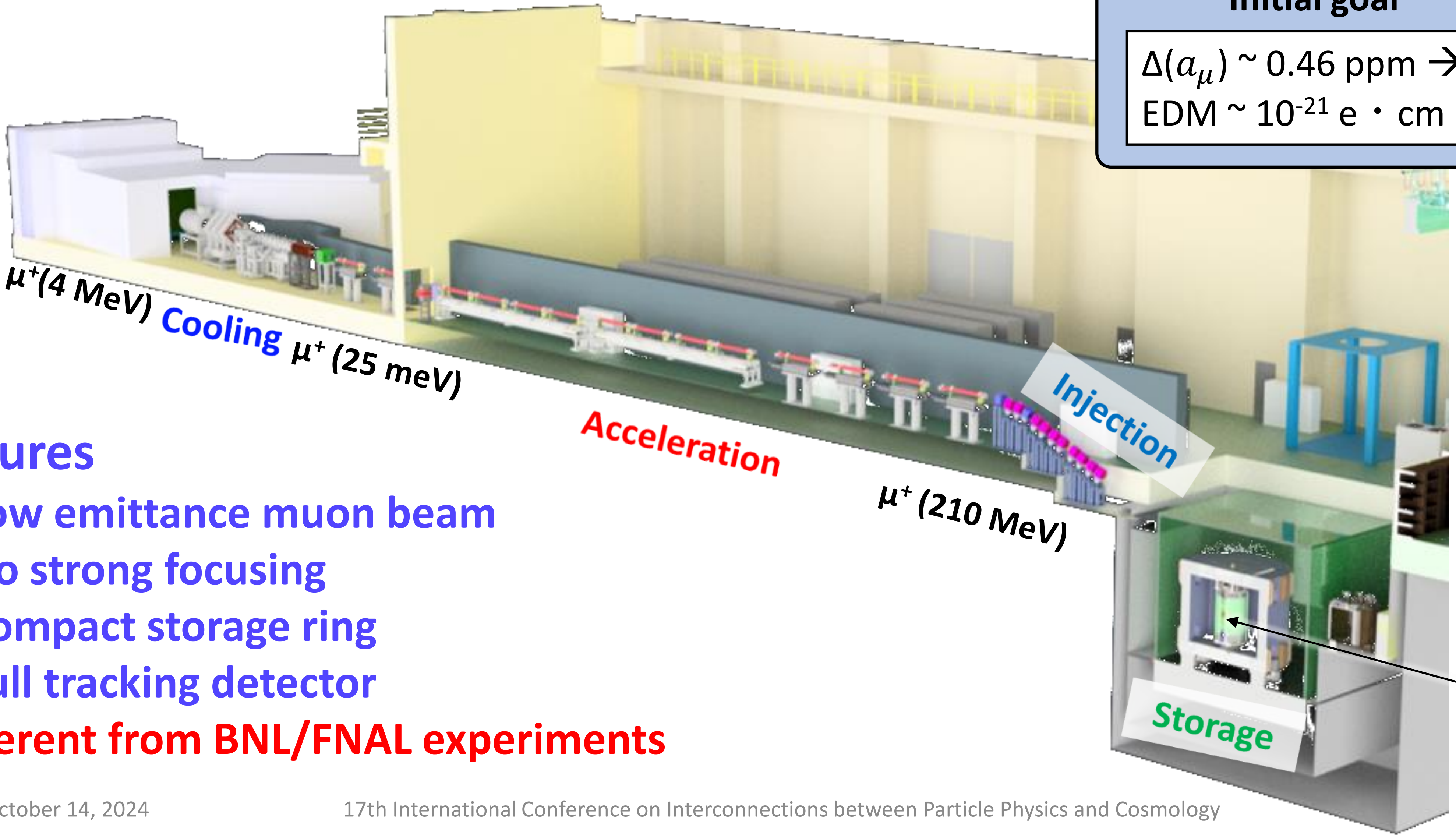
Radius of cyclotron motion: 7.1 m

Radius of cyclotron motion: 333 mm

PTEP 2019 (2019), 053C02

J-PARC E34 Experiment

	Initial goal	Final goal
$\Delta(a_\mu)$ ~	0.46 ppm →	0.1 ppm
EDM ~ 10^{-21} e・cm		



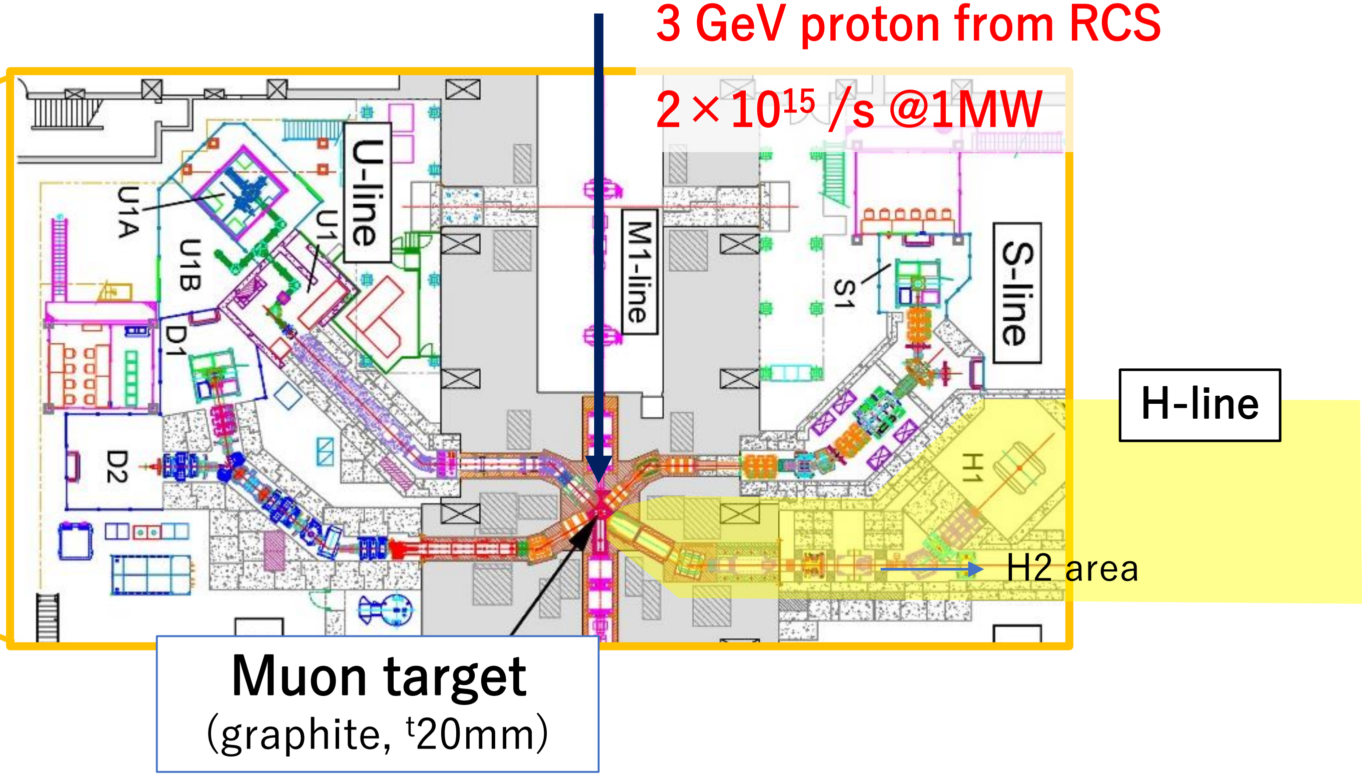
Features

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

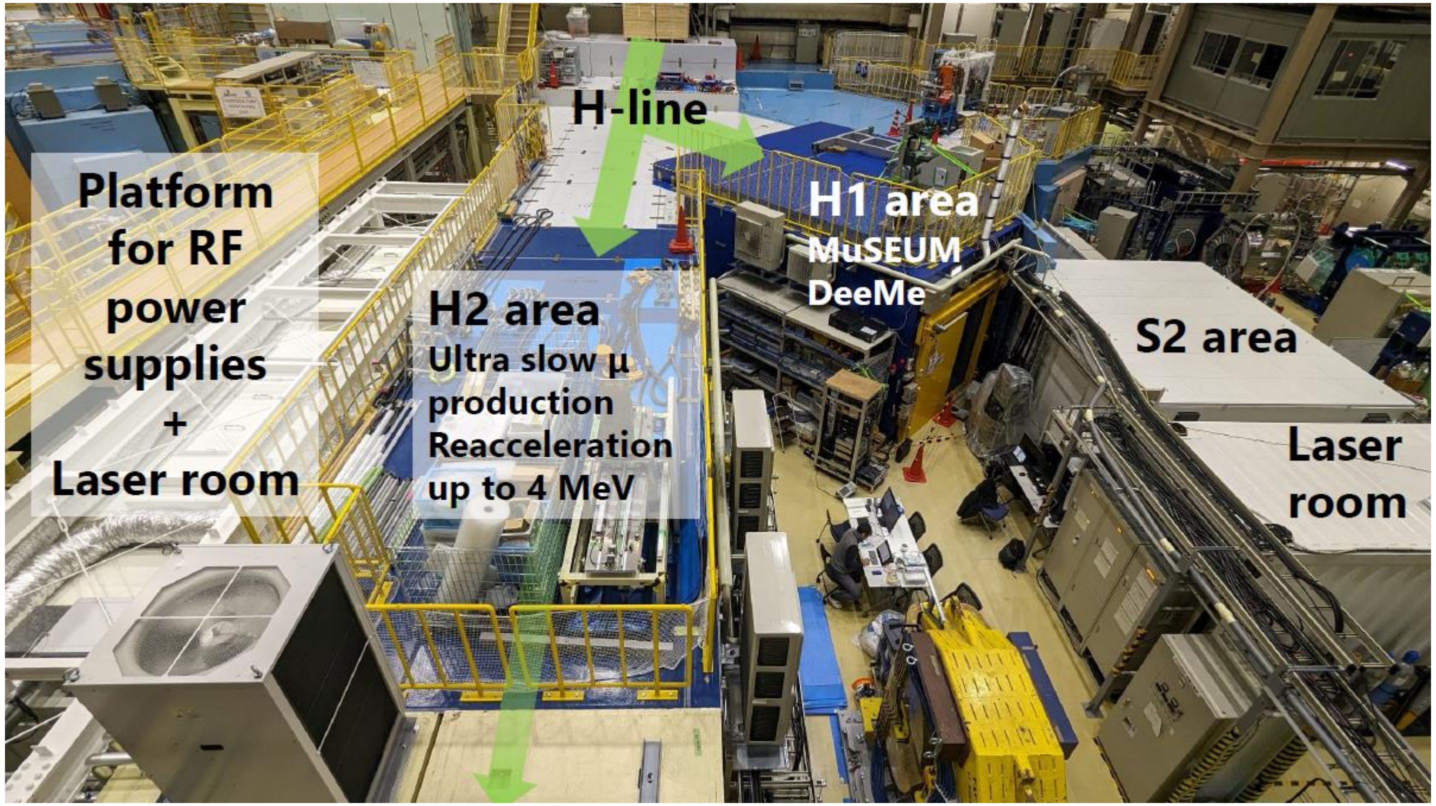
Different from BNL/FNAL experiments

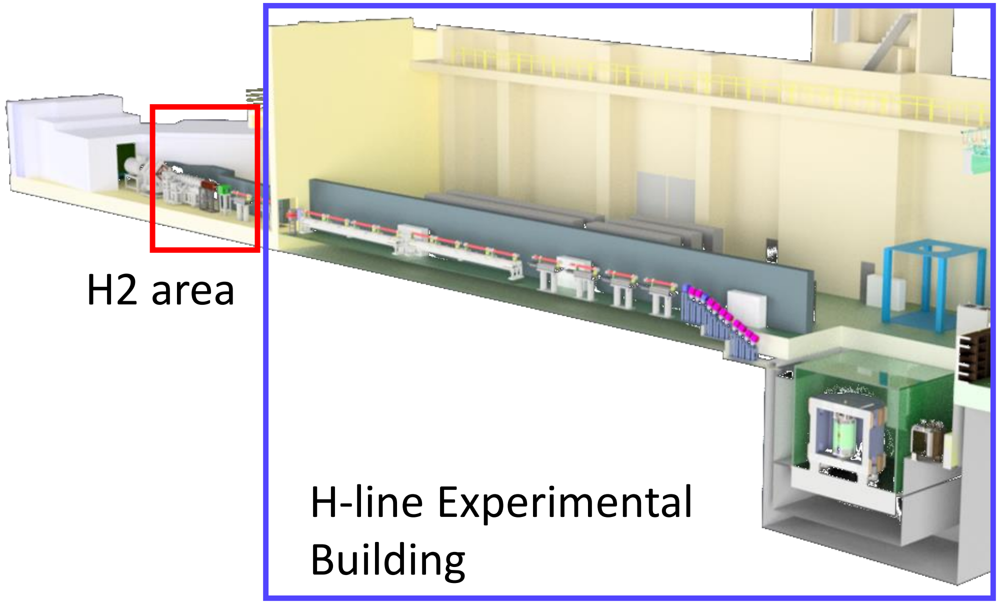
J-PARC MLF H-line

- A new beam line (H-line) at J-PARC MLF will be used for the experiment.



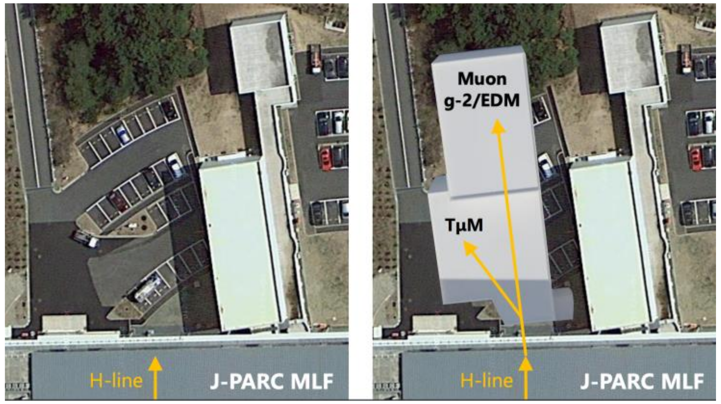
H-line Construction Status





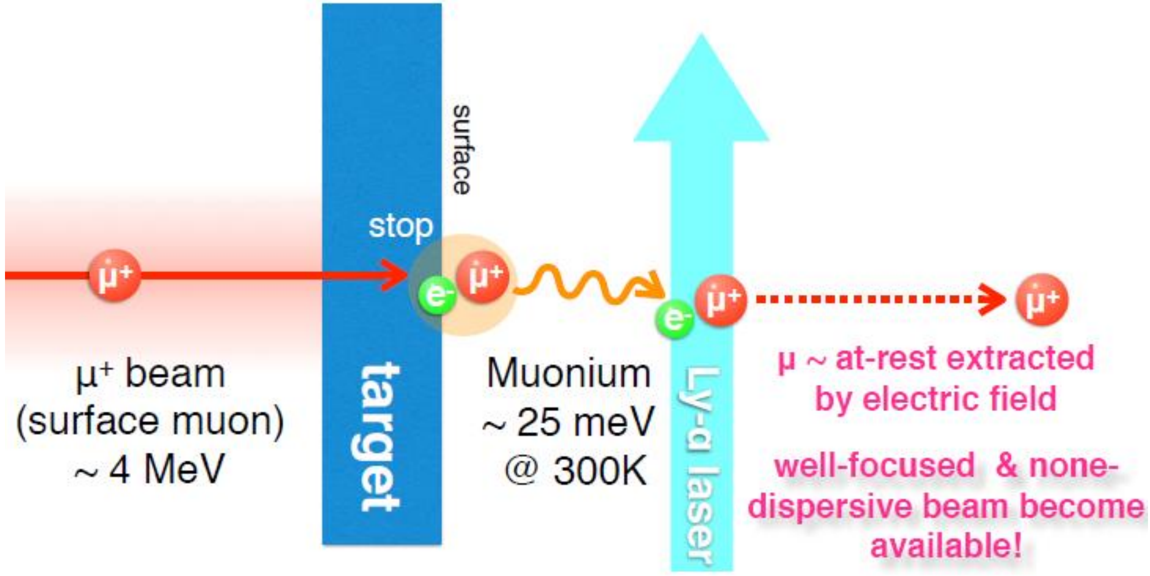
- H1 area construction has been finished.
- Construction of H2 area is being conducted.

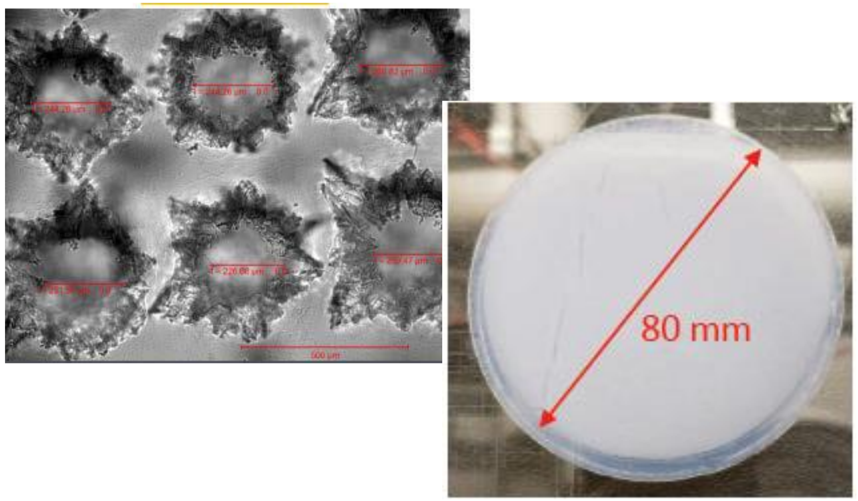
Engineering design of a new building for the experiment is also ongoing.



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 μ^+) 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.

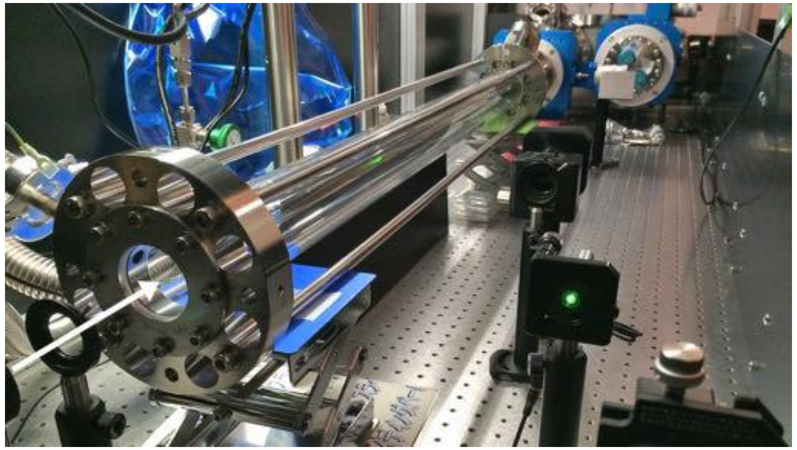




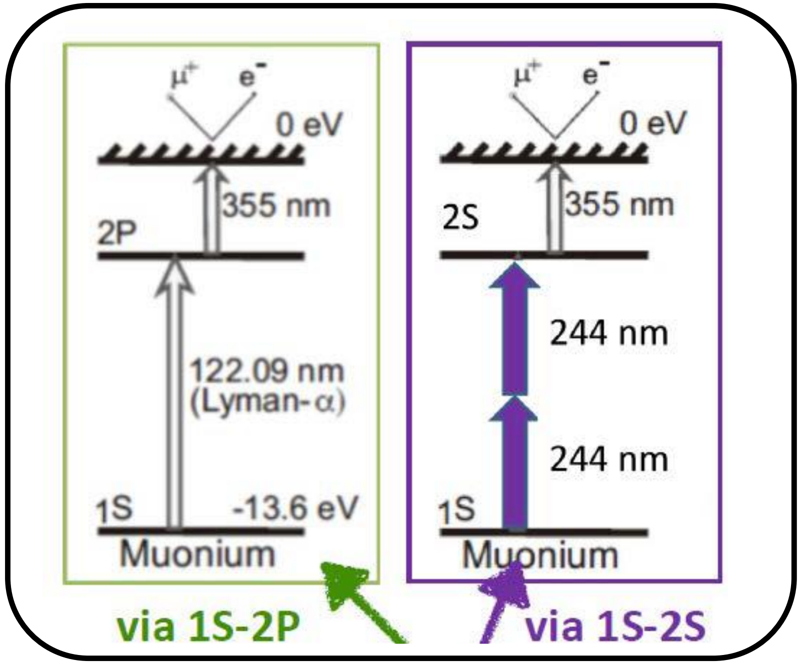
Silico aerogel target installed in S-line of J-PARC MLF

Muonium Ionization

- In the original design, an intense Lyman-α laser (122 nm) and 355 nm laser will be used to ionize muonium via 1S-2P transition.
  - Laser power of 100 μJ is needed for Lyman-α laser.
  - Improvement of laser power is expected by recent laser upgrade.
- As an alternative method, ionization scheme with 244 nm laser is being developed collaborating with the muonium 1S-2S spectroscopy measurement experiment.

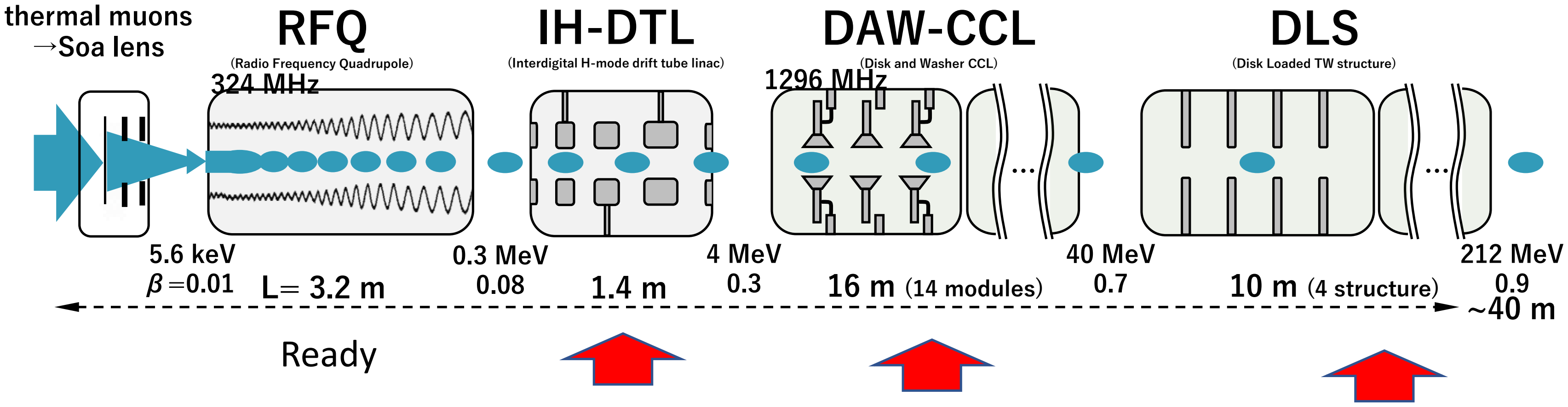


Lyman-α laser system

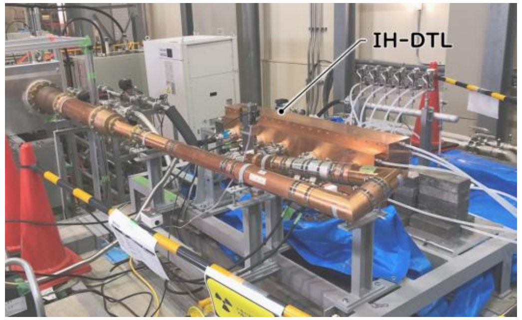


Muon Acceleration

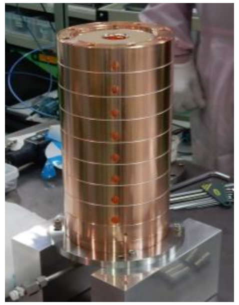
- Thermal muon beam is accelerated to p=300 MeV/c in LINAC.
- Different types of acceleration cavities are utilized to cover wide range of velocity.



Fabrication was completed and high power test was successfully done.



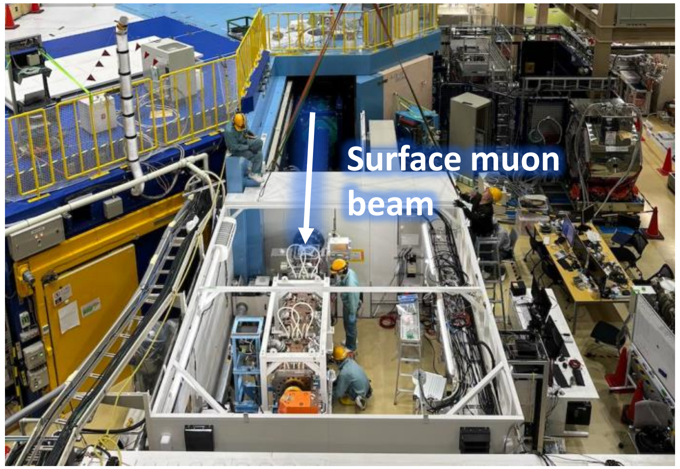
Fabrication method of the tank module was established.



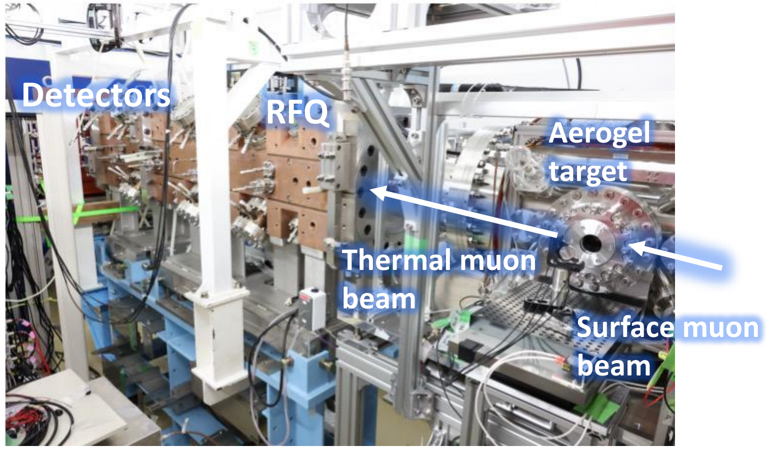
1st tube prototype was fabricated.

Demonstration of Muon Acceleration

- Thermal muon production and its acceleration was demonstrated in this spring.
- Currently available facilities/instruments were used instead of the real ones.
  - S2 area (surface muon line) instead of the H2 area
  - 244 nm Ionization laser to utilize 1S-2S transition
  - Prototype RFQ (shorter version) due to limitation of experimental area

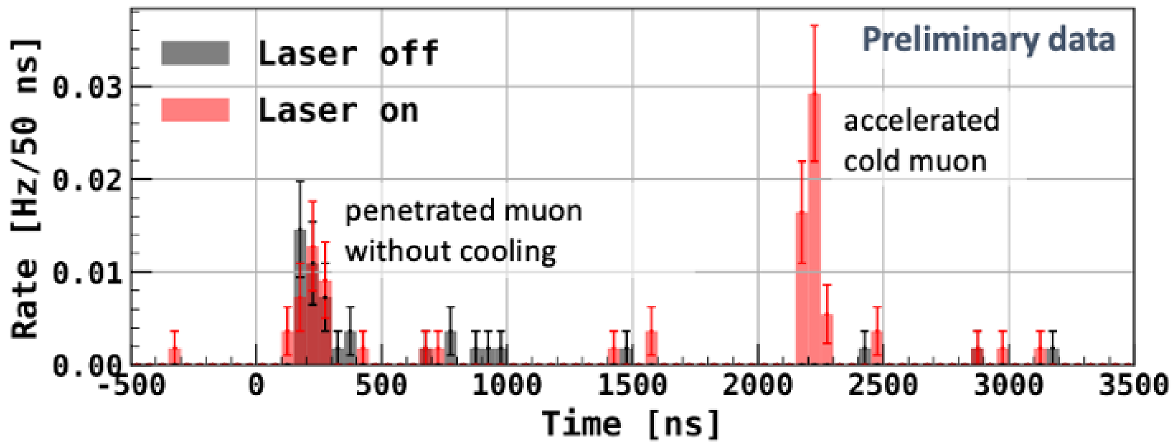


J-PARC MLF S2 area

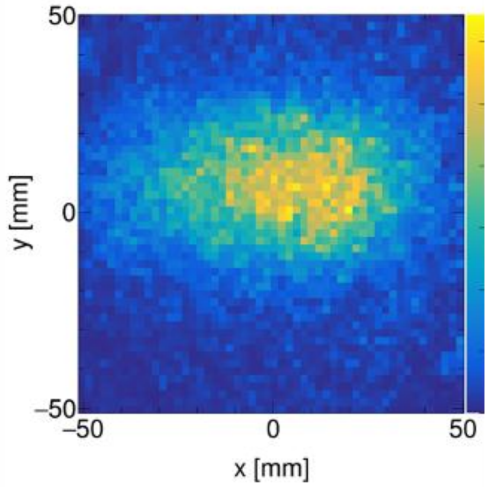


Result of Muon Reacceleration

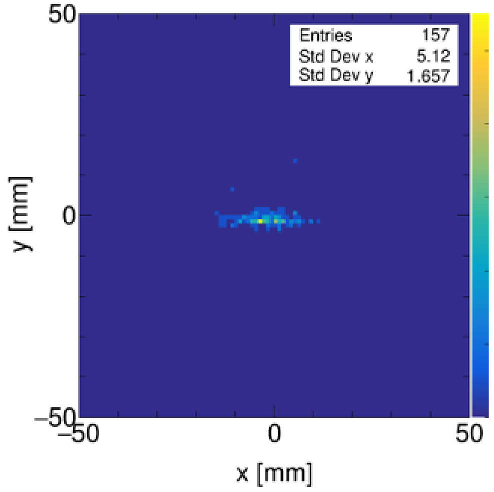
- **The world's first cooling and acceleration of muon is achieved.**
  - Beam profile before and after the cooling/accelerating were taken
  - Qualitative evaluation of the emittance underway.
  - Press release available at https://j-parc.jp/c/en/press-release/2024/05/23001341.html
  - Scientific paper is in preparation.



Time of flight from muon on target



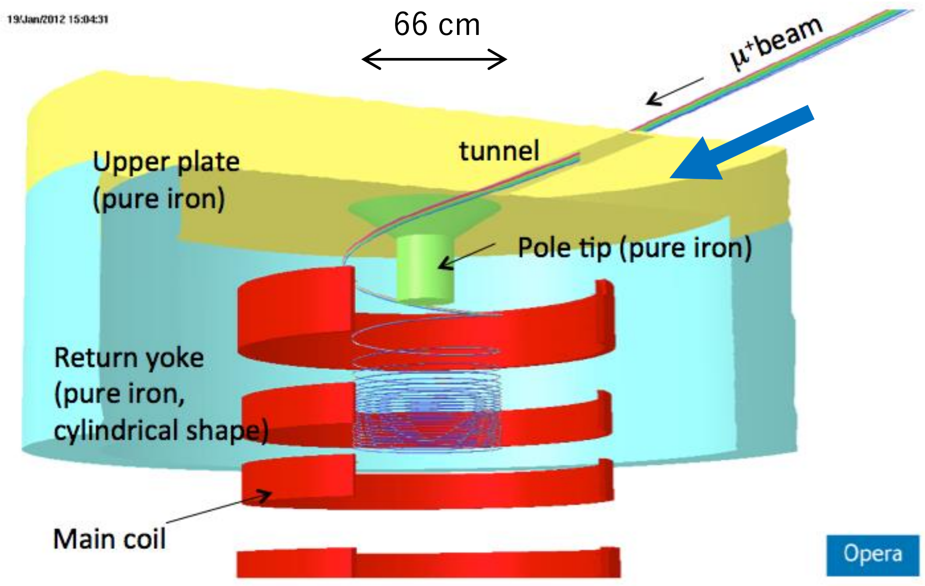
Beam profile before cooling



After reacceleration

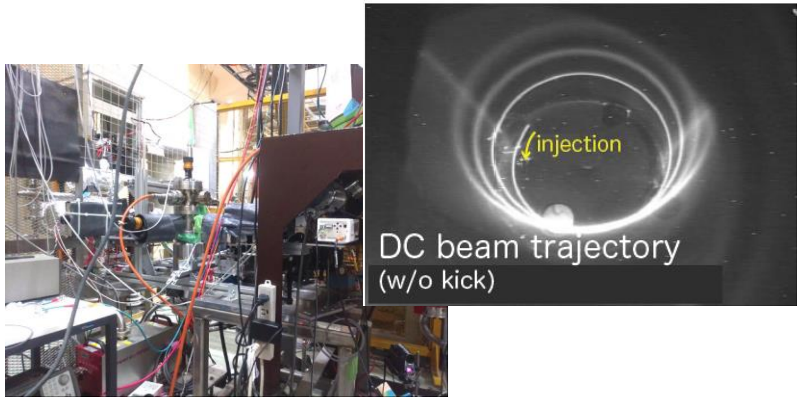
3D Spiral Injection

- 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.

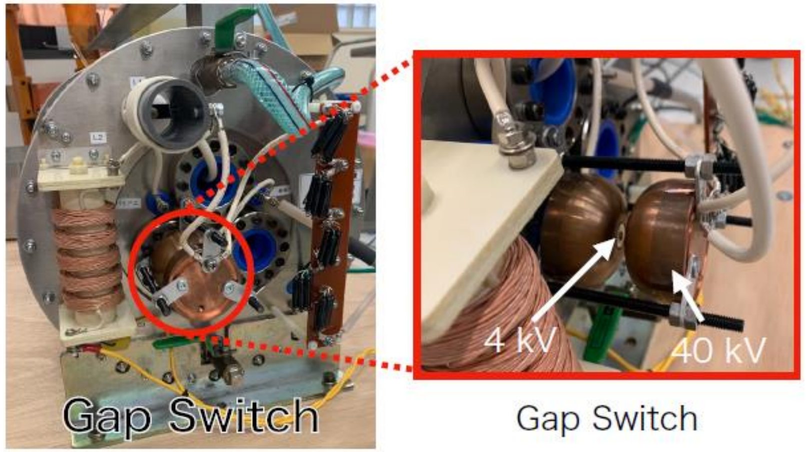


3D spiral Injection orbit

Real scale prototype of kicker coils



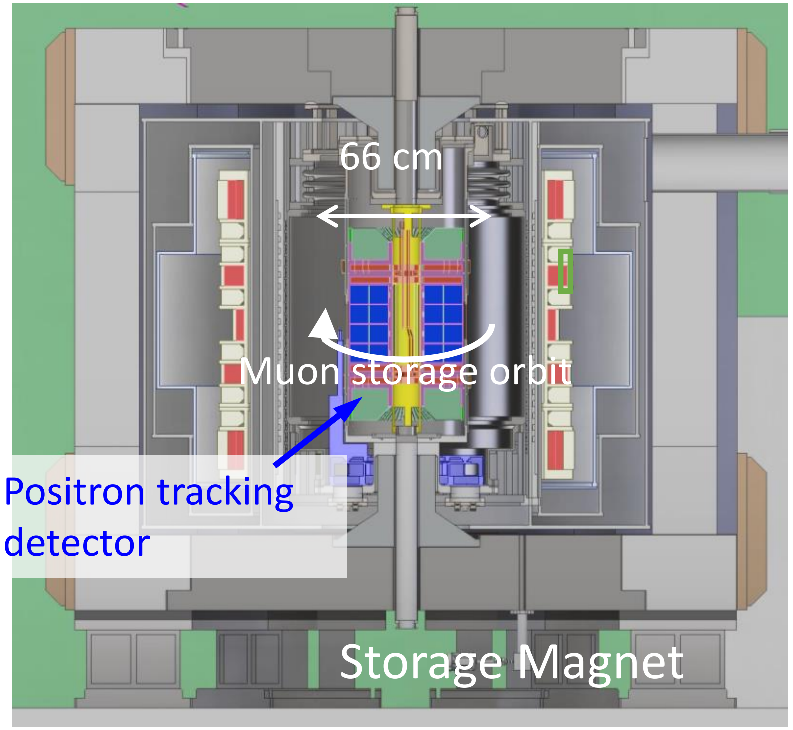
Injection test with DC electron beam

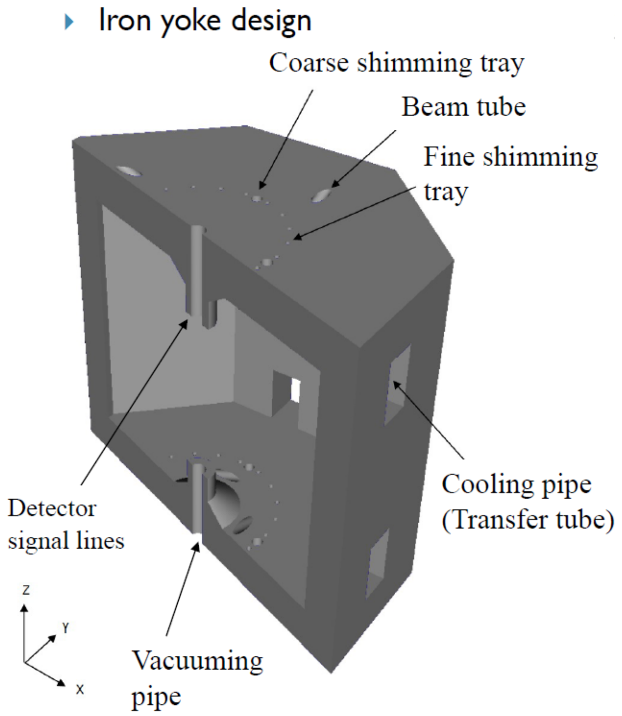


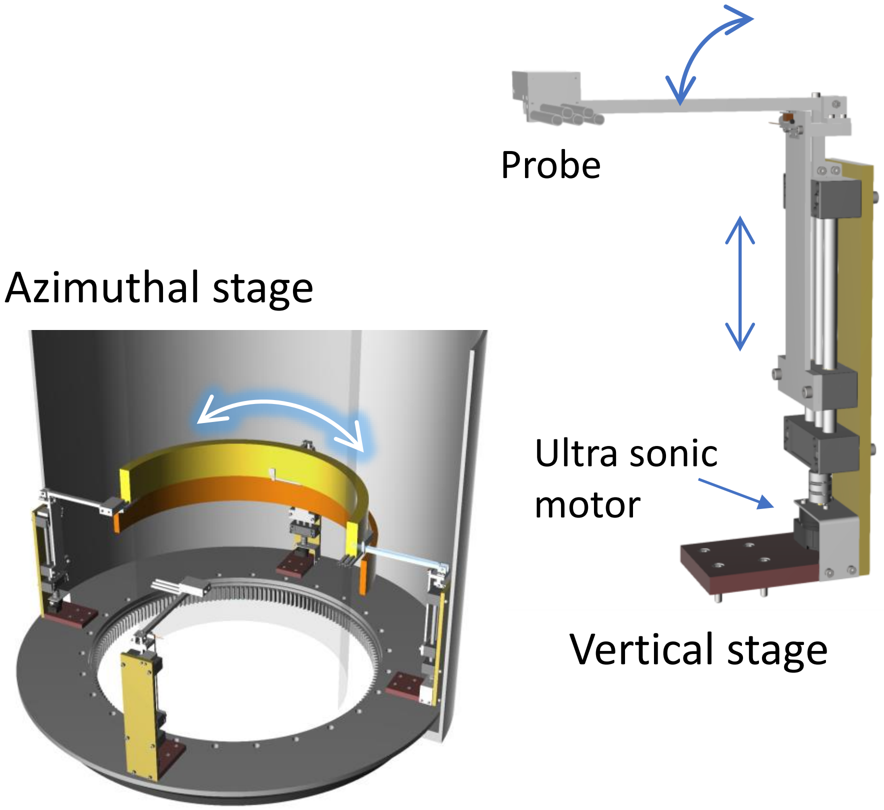
Pulse power supply for prototype kicker coils

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.



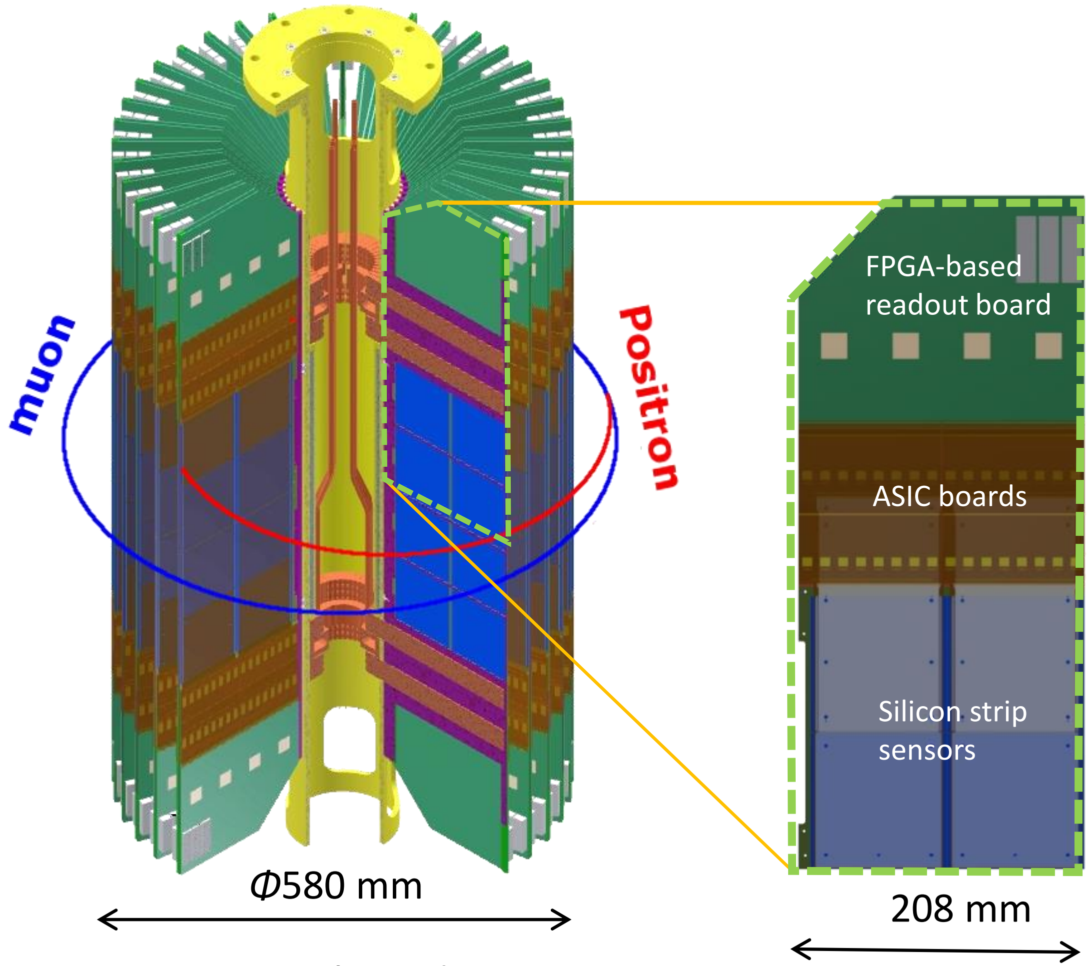




Moving stages for field monitoring

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 µm pitch silicon strip sensor
  - 5 ns sampling rate in readout ASIC



Positron tracking detector

1/4 vane

Detector Assembly and Quality Control Test

- Detector assembly methods are being developed at KEK and Kyushu University.
- Inspection of readout ASICs was conducted at Kyushu University and completed.

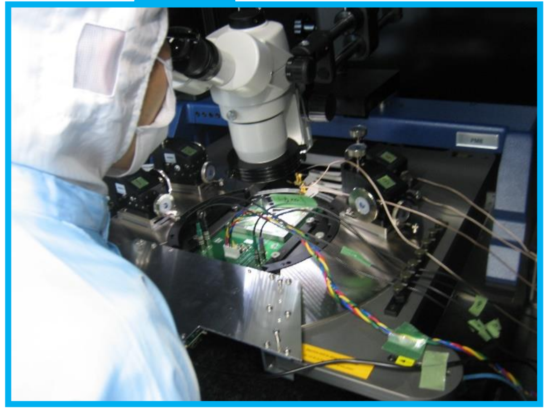
Semiconductor detector development facility at Kyushu University

Sensor assembling jig

Detector assembly room at KEK

3D coordinate measuring machine

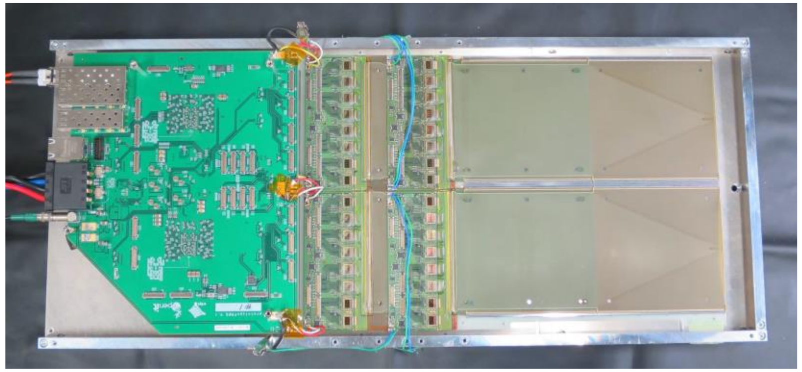
Wire bonding operation



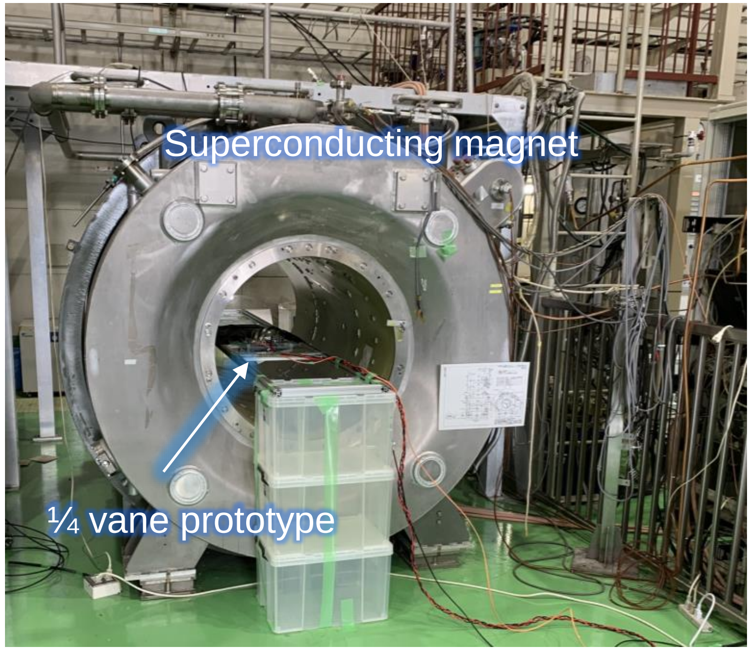
Inspection of readout ASIC

Detector Operation Tests

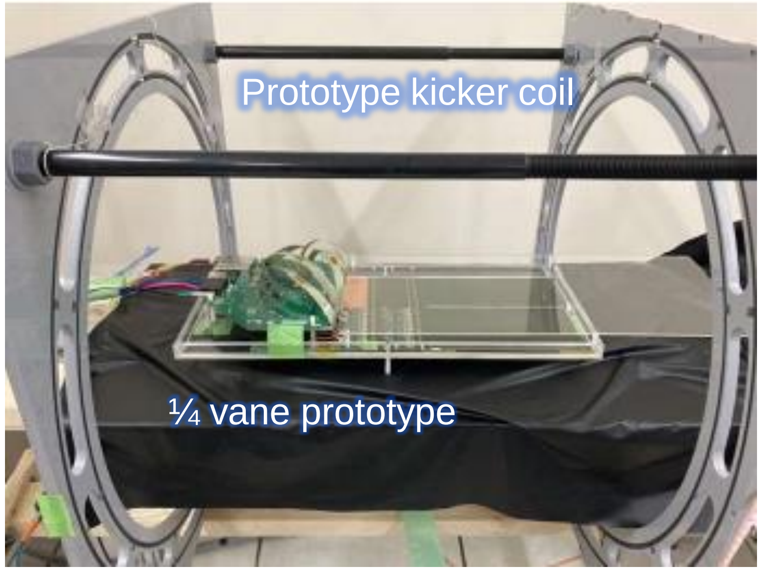
- Several prototype modules were produced.
- Operation tests of readout boards and a prototype detector module were performed under various conditions.



¼ vane prototype



Operation test in high magnetic field

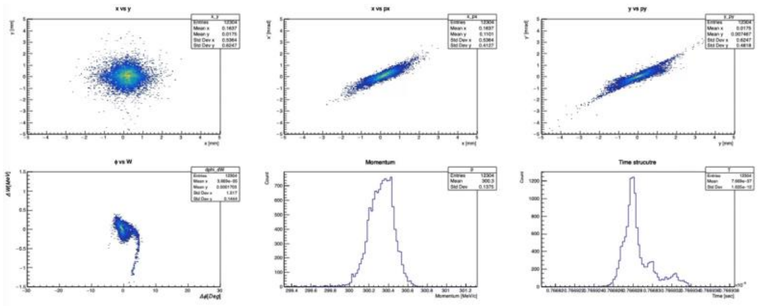


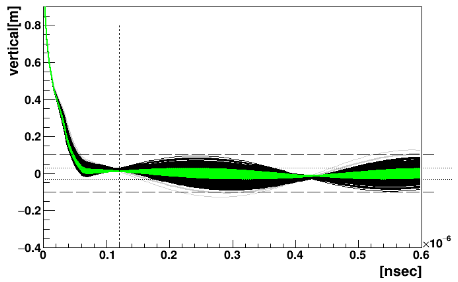
Operation test in kicker magnetic field

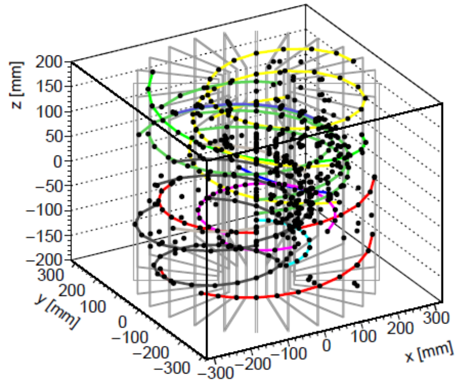
Operation test in vacuum

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 at KEK Computing Center.



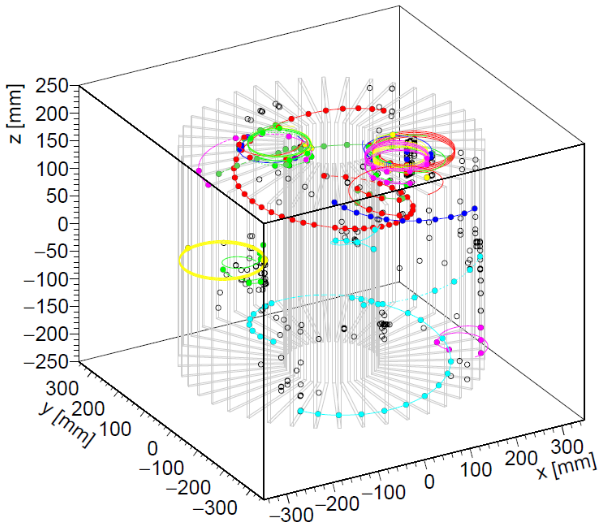




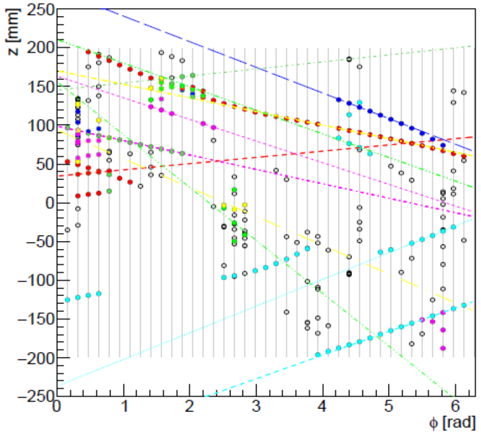
Surface muon → **Thermal muon** → **Acceleration** → **Transport & Injection** → **Storage** → **Detection** → **Reconstruction**

Track Reconstruction

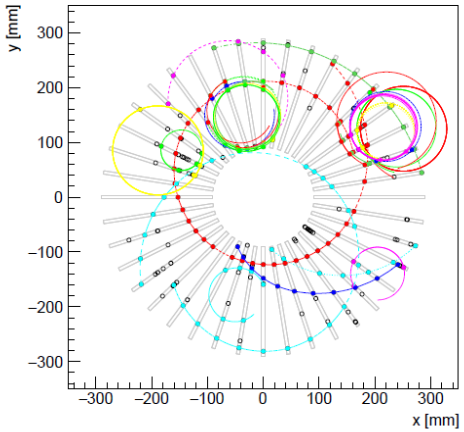
- One of the challenges in software is track reconstruction speed.
  - At the actual experiment, ~3×10^4 signal tracks/s will be detected.
- High speed track reconstruction algorithm based on Hough transform in z-ϕ plane has been developed.
  - But still, another factor of improvement is desired to process data within ~1000 CPUs.
  - Introduction of new technologies such as Graph Neural Network and GPU are ongoing collaborating with IITH and Central University of Karnataka.



Event display of detector (corresponding to ~one time window)



Projection to z-ϕ plane
- High momentum tracks leave hits on a straight line.



Top view of the detector

Experiment Status

114 members from Canada, China, Czech, France, India, Japan, Korea, Netherlands, Russia, USA

28th Collaboration Meeting in June 2024@J-PARC

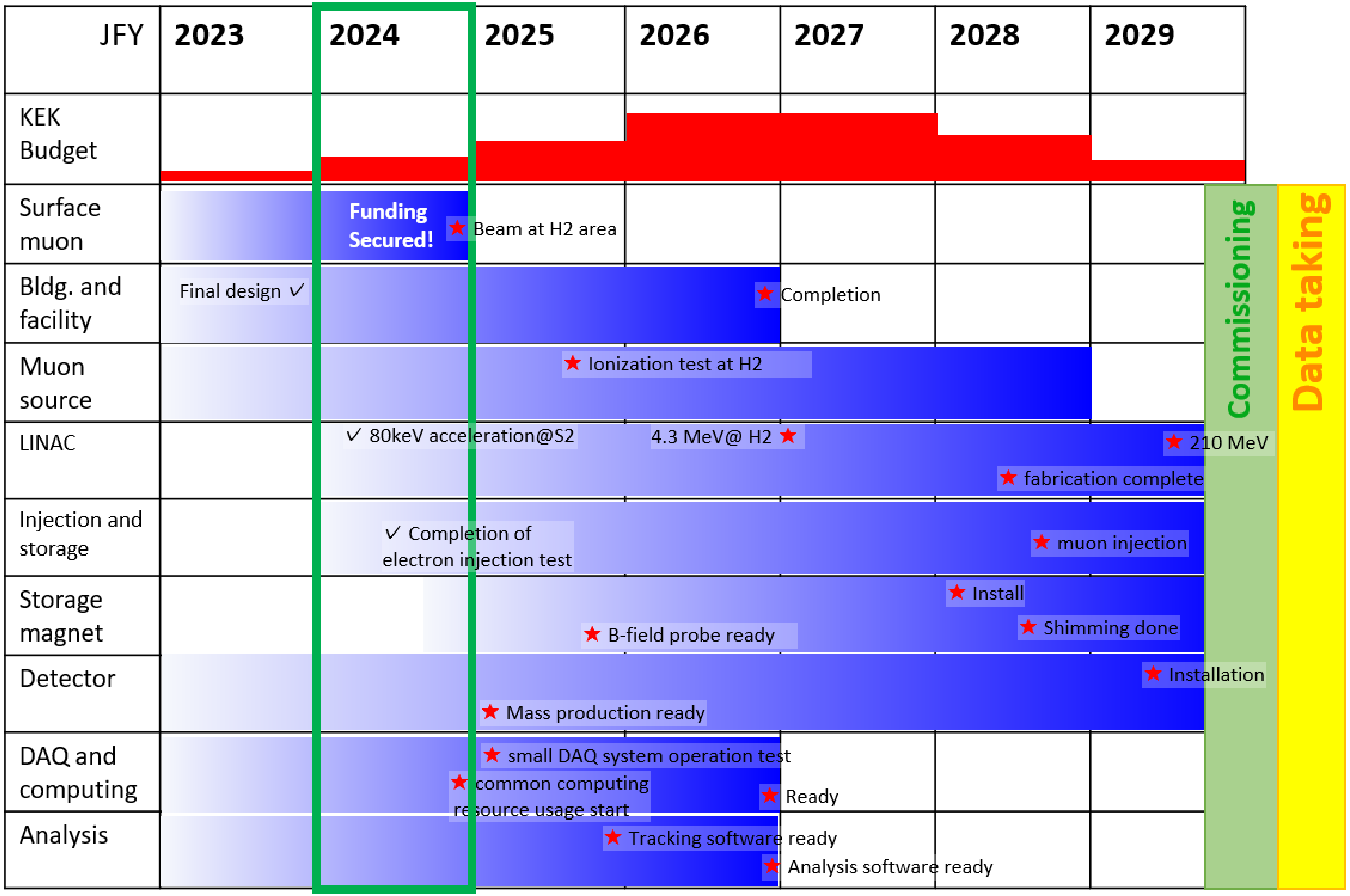
Year	Funding
2020	• Grant-in-Aid "Specially Promoted Research" (2020-2025)
2022	• Funding to prepare for construction
2023	• Funding to prepare for construction
2024	• Funding to complete H-line extension • K-program (2024-2028)

KEK plans to request funding for remaining parts including

- H-line experimental building
- Muon LINAC / Injection
- Storage magnet, etc.

Schedule

- Construction of experimental apparatus is ongoing.
- We are aiming at the start of commissioning from 2029 JFY.



Summary

- In the J-PARC E34 experiment, measurement of muon g-2 and EDM is planned with a method different from BNL/FNAL experiments.
- Recently, acceleration of thermal muon beam was demonstrated at J-PARC.
- Preparation of the experiment is ongoing aiming at the start of the commissioning in 2029 JFY.