J-PARC muon g-2/EDM experiment

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May 17th 2025

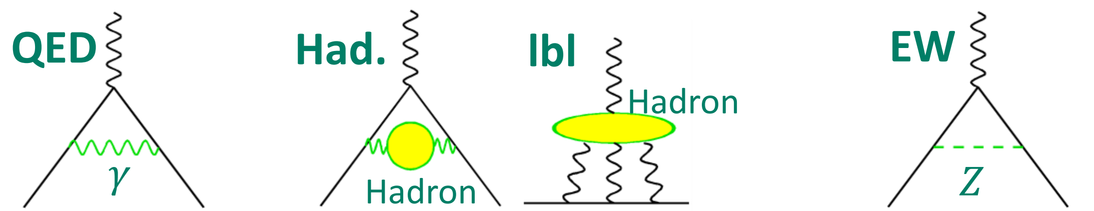
on behalf of the J-PARC muon g-2/EDM collaboration

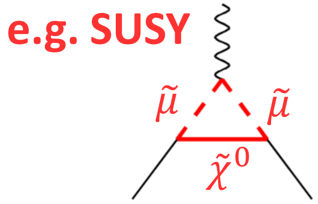
@MIP20025

Muon g-2 and EDM

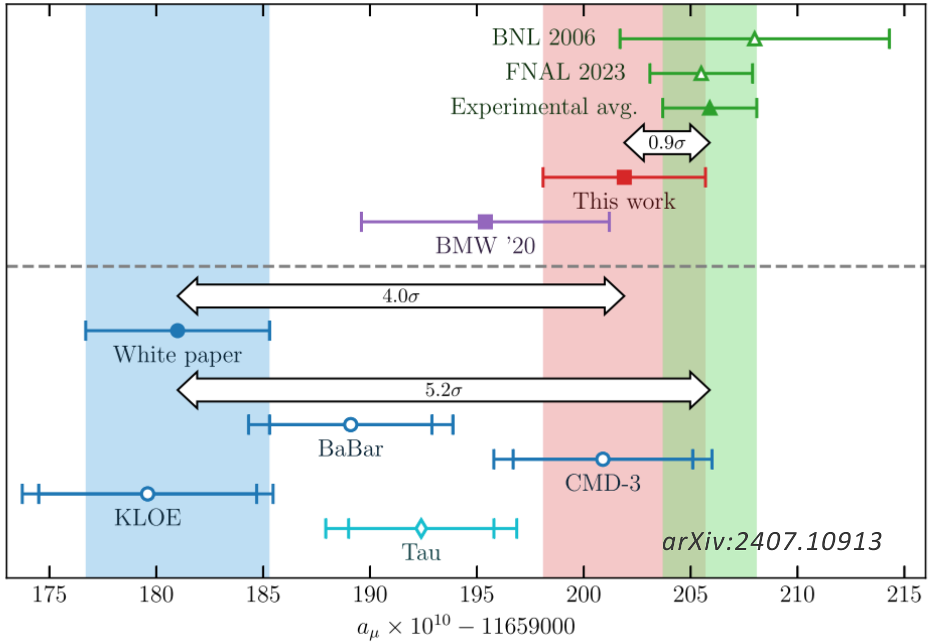
Anomalous magnetic moment (a_μ, g-2)

- Deviation of “*g*-factor” from the prediction of the Dirac equation for fermions.
  - $a_\mu \equiv \frac{g-2}{2} = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{had}) + a_\mu(\mathrm{weak}) + a_\mu(\mathrm{New\ Physics})$





- >5σ deviation between the Standard Model prediction (white paper) and measurements.



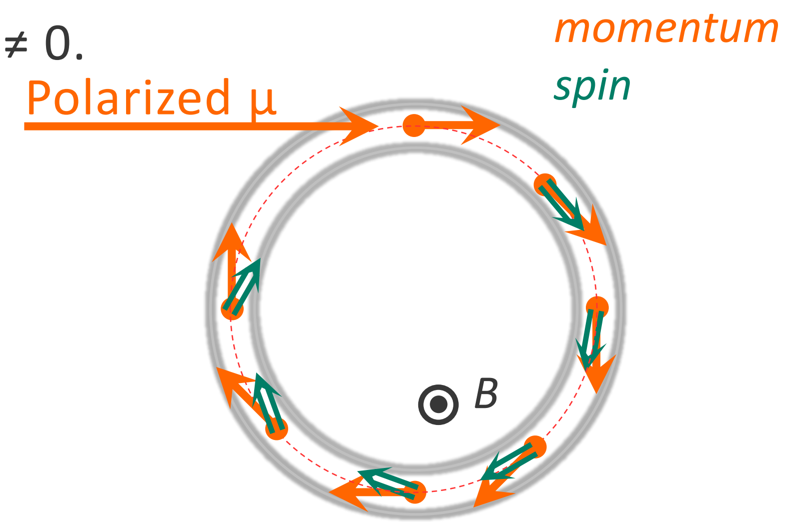
Electric Dipole Moment (EDM)

- Non-zero EDM indicates T-violation.
  (It is equivalent to CP-violation in CPT theorem.)
- Upper limit : $d < 1.8 \times 10^{-19} e \cdot \mathrm{cm}$ (95% C.L.) by BNL E821.

➢ **A new experiment to measure muon g-2 and EDM at J-PARC**

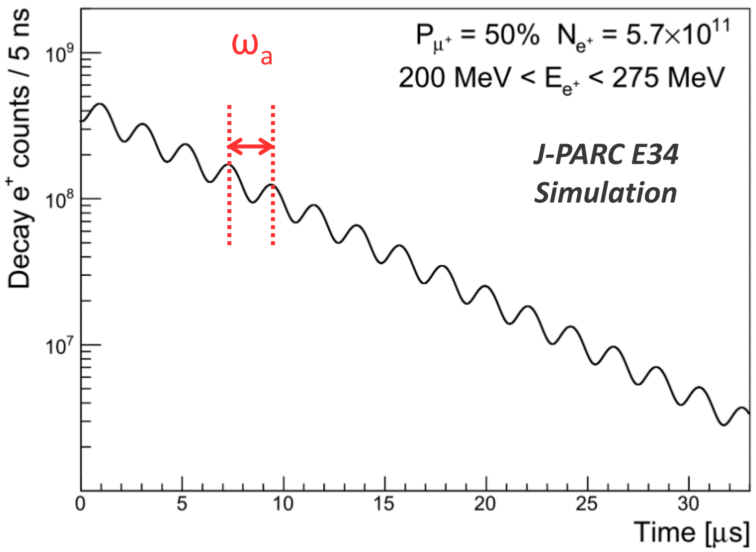
Measurement Principle

- In uniform B-field, muon spin rotates ahead of momentum due to g-2 ≠ 0.
- Anomalous precession : Spin precession vector w.r.t momentum

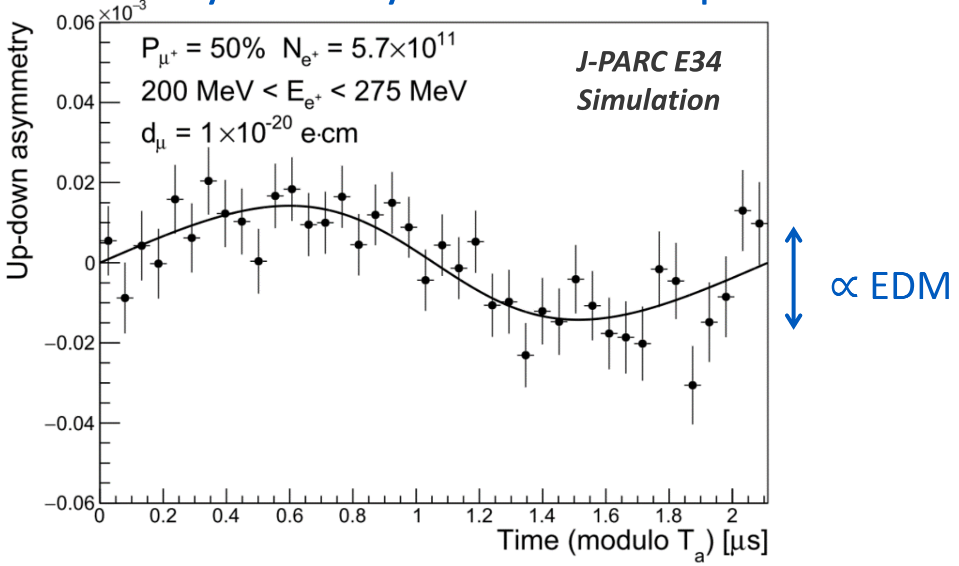


$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$
$$= -\frac{e}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\text{EDM term}}\right]$$

Number of detected positron

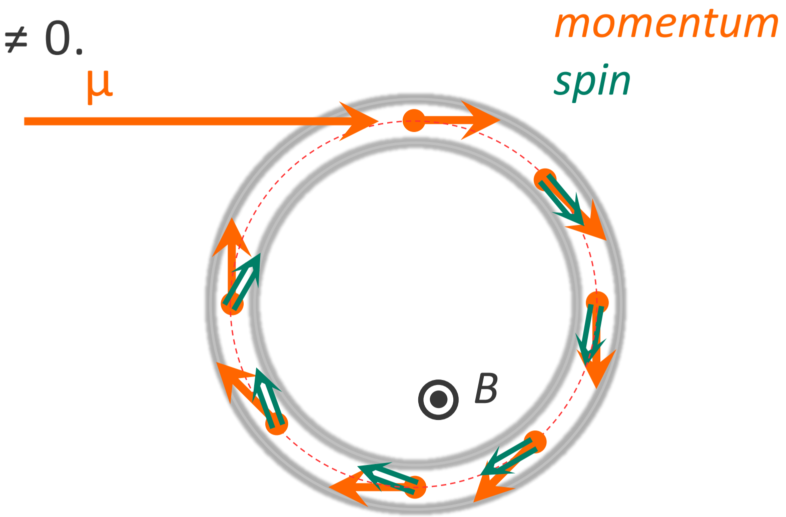


Up-down asymmetry of detected positron



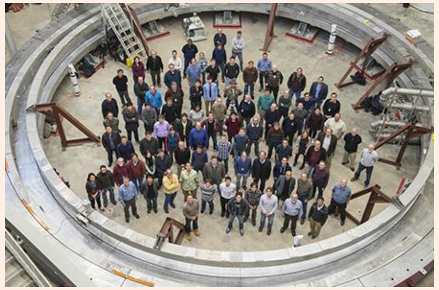
Experimental Approaches

- In uniform B-field, muon spin rotates ahead of momentum due to g-2 ≠ 0.
- Anomalous precession : Spin precession vector w.r.t momentum



$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$
$$= -\frac{e}{m_\mu}\Bigg[\underbrace{a_\mu \vec{B} - \overset{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\frac{\vec{\beta}\times \overset{0}{\vec{E}}}{c}}_{\text{g-2 term}(\boldsymbol{\omega_a})} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\overset{0}{\vec{E}}}{c}\right)}_{\text{EDM term }(\boldsymbol{\omega_\eta})}\Bigg]$$

BNL E821 & FNAL E989

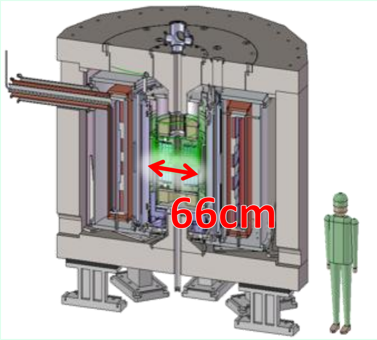


- Magic momentum

  $\gamma = 29.3 \ (p = 3.1 \ \mathrm{GeV}/c)$
- Weak electric focusing.

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

J-PARC E34



- No electric field
- Very weak magnetic focusing

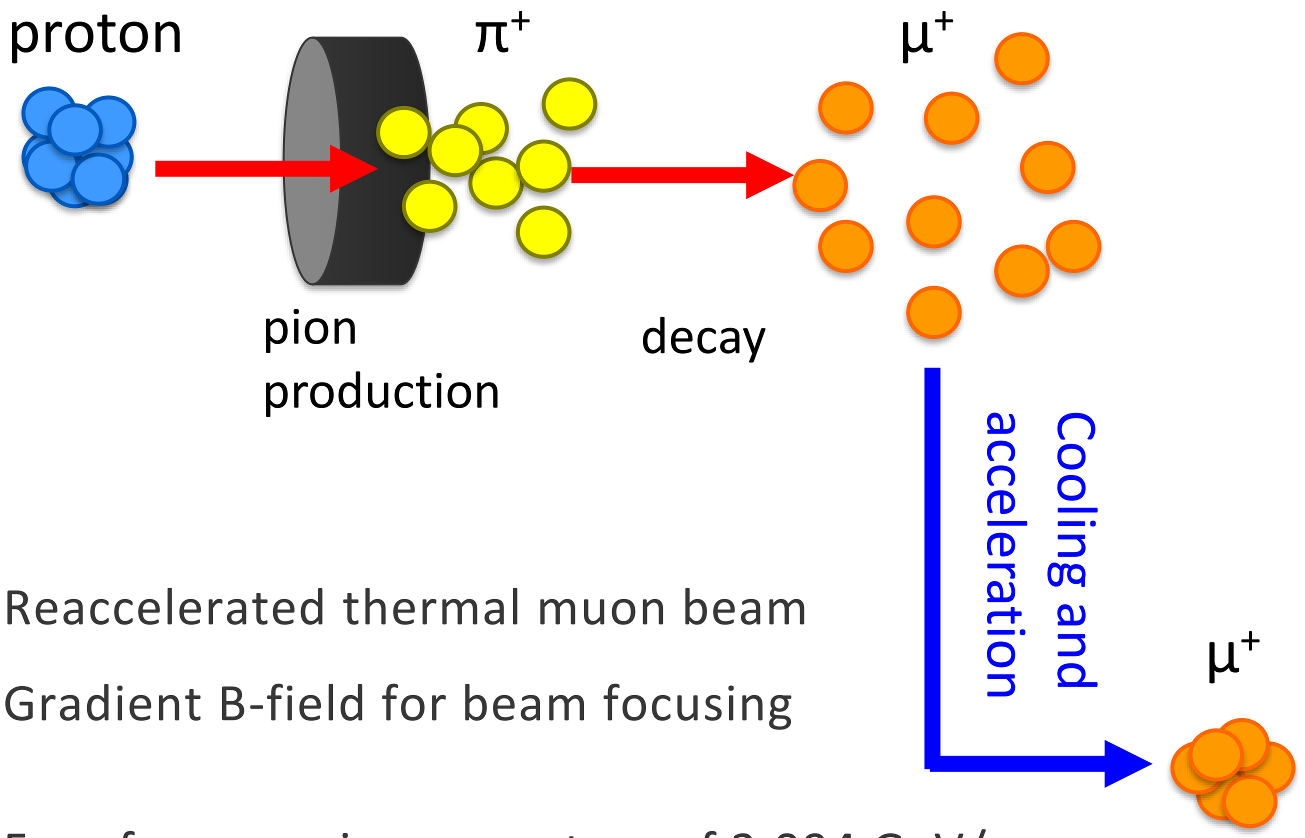
$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

$p = 300 \ \mathrm{MeV}/c$

→ **Different systematic uncertainty.**

→ **Clear separation of $\vec{\omega}_a$ and $\vec{\omega}_\eta$.**

Reaccelerated thermal muon beam



Conventional muon beam

(Emittance ~ 1000π mm・mrad)

- Strong focusing with electric field
- Muon loss
- Pion background

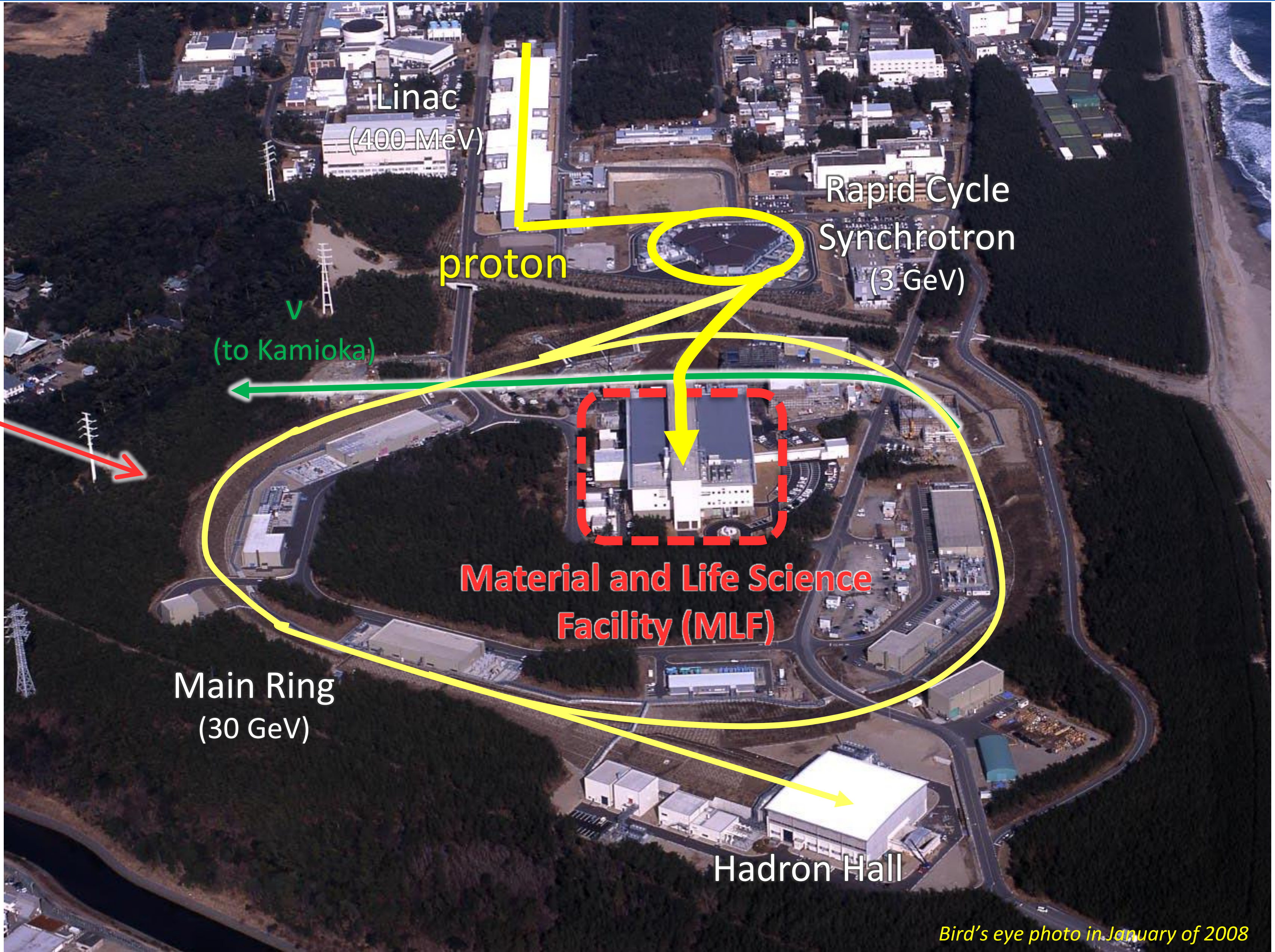
Reaccelerated thermal muon beam

(Emittance ~ 1π mm・mrad)

- ➢ **Free from any of the above**

- Reaccelerated thermal muon beam
  - ➢ Gradient B-field for beam focusing
- Free from magic momentum of 3.094 GeV/c
  - ➢ Lower momentum beam of 300 MeV/c
    - Compact storage ring with excellent uniformity (Δ~0.1 ppm)
    - Full tracking detector for decay positron

J-PARC Proton Accelerator Research Complex (J-PARC)



J-PARC muon g-2/EDM Experiment

① Muon Beam Line and experimental area

② Thermal muon

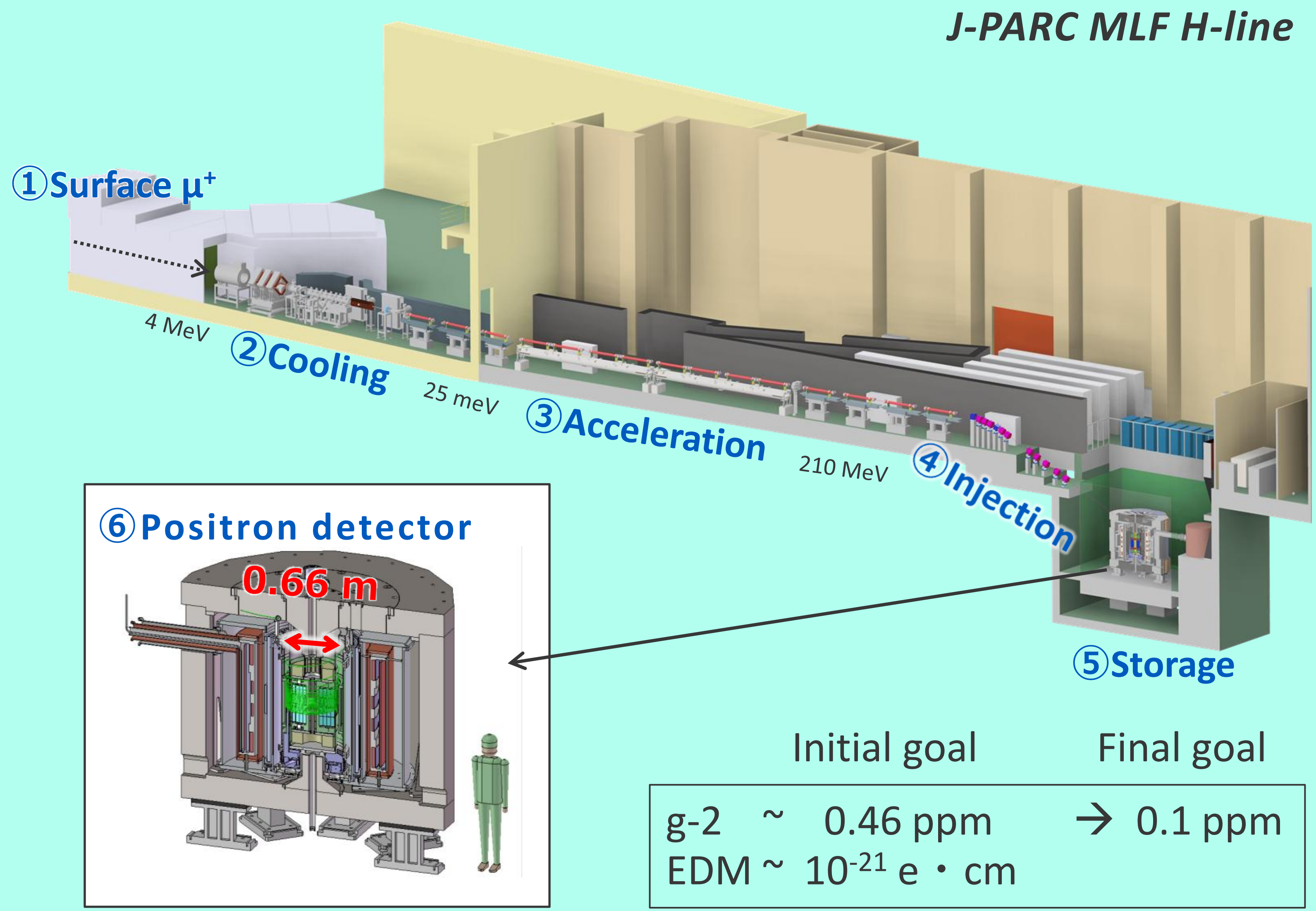
③ Muon linac

④ Injection

⑤ Storage

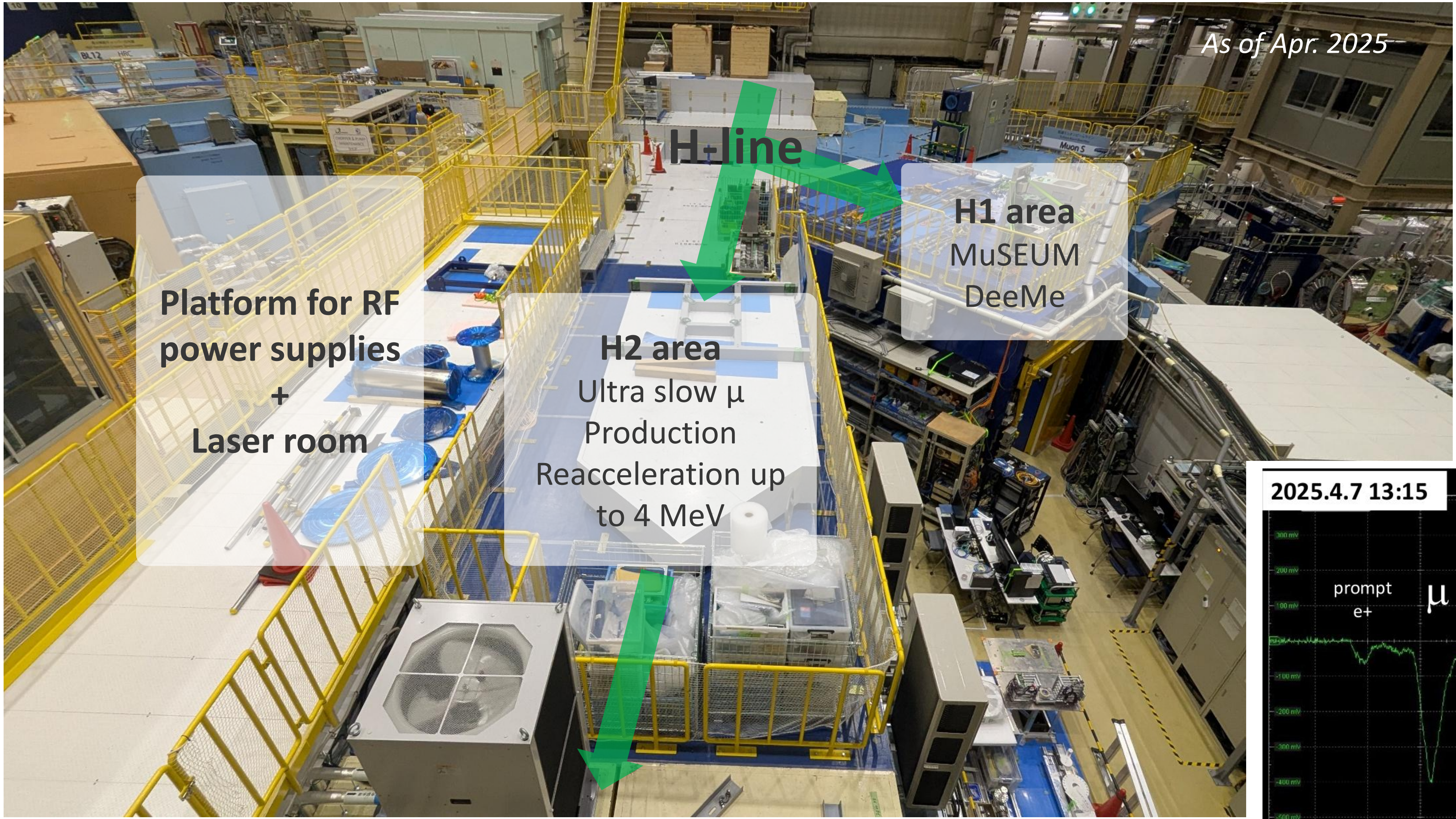
⑥ Detector

- Construction of facility has been started in 2022.
- Aiming for data taking from 2030.

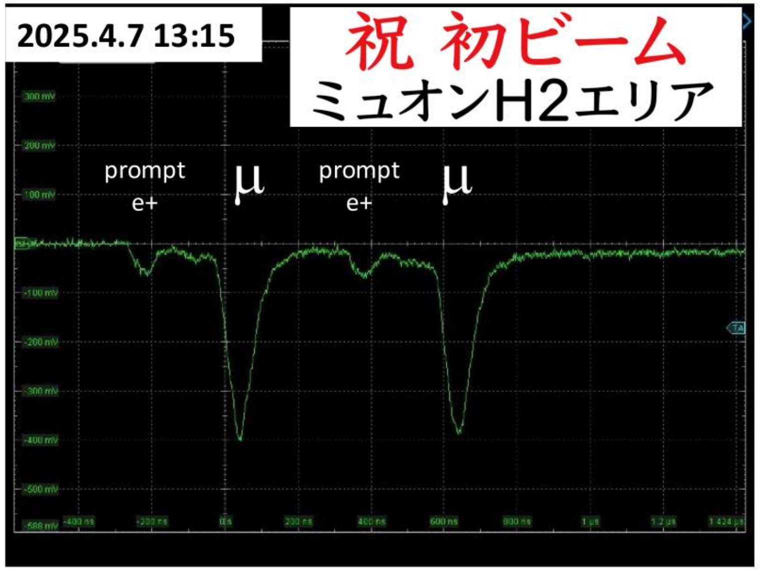


	Initial goal	Final goal
g-2	~ 0.46 ppm	→ 0.1 ppm
EDM	~ 10^{-21} e・cm	

① Muon Beam Line and Experimental Area



First beam was delivered to H2 area

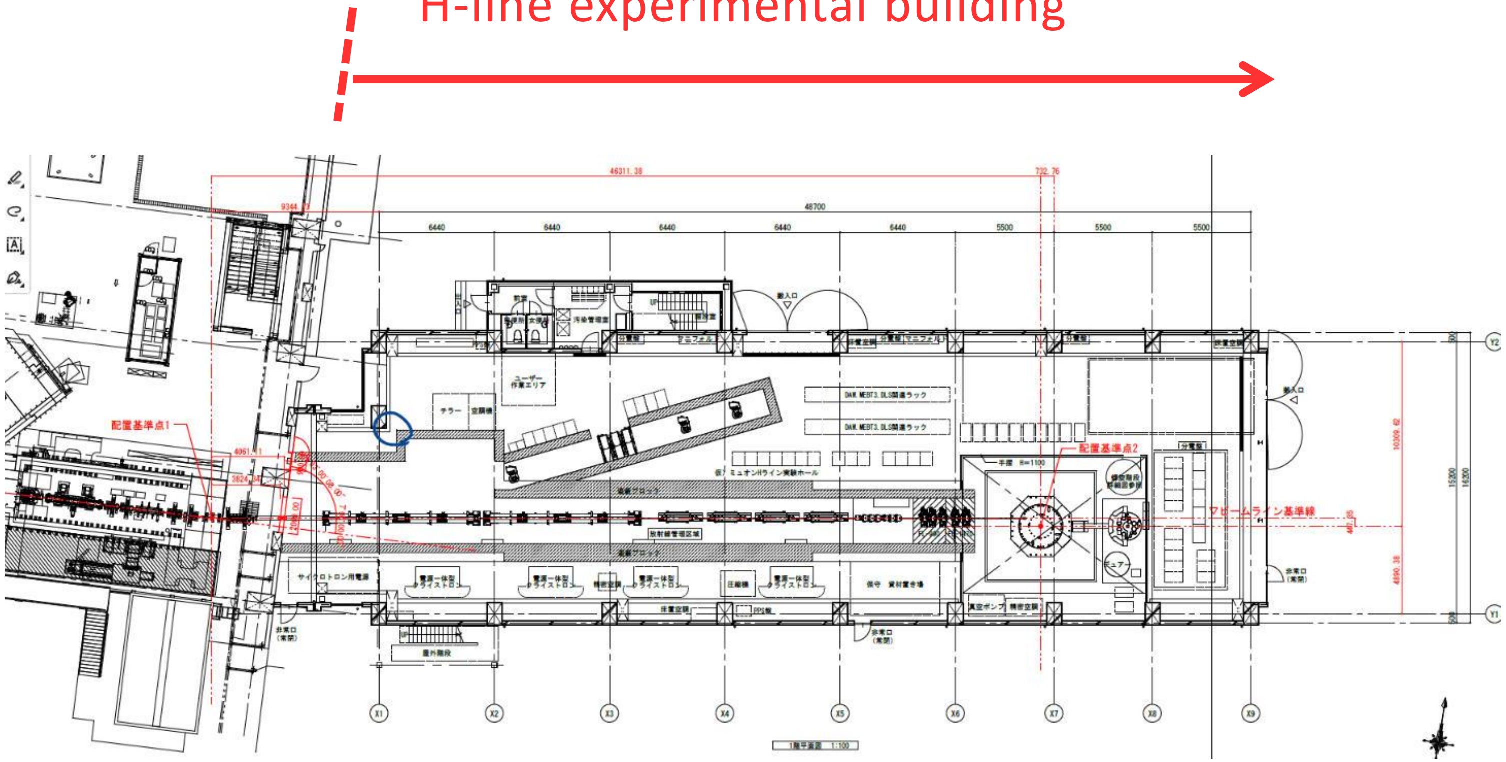


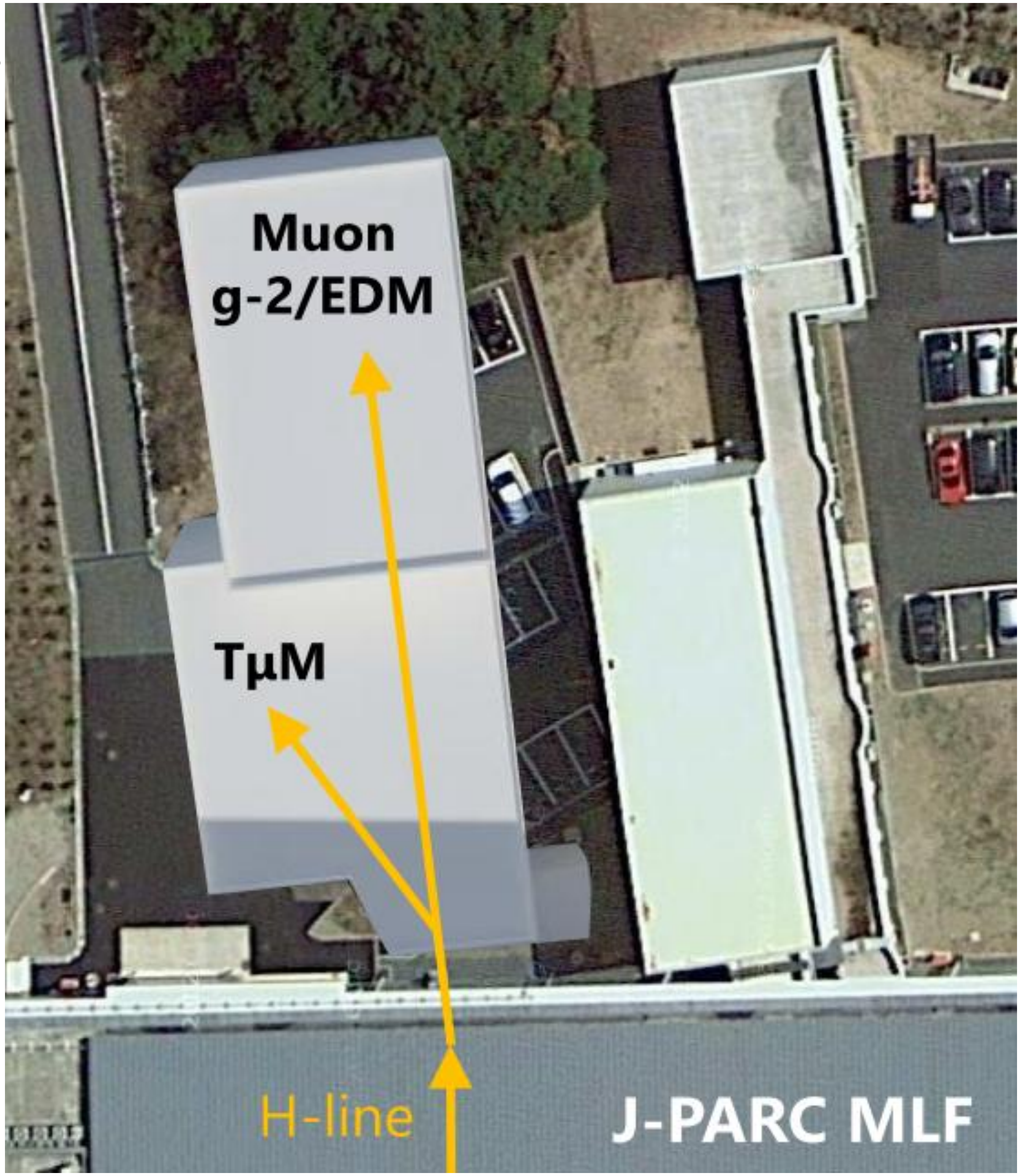
Future extension to accelerate up to 212 MeV

① Muon Beam Line and Experimental Area

- Experimental building for H-line will be newly constructed.
- Design work is underway to reduce the construction costs of the building.

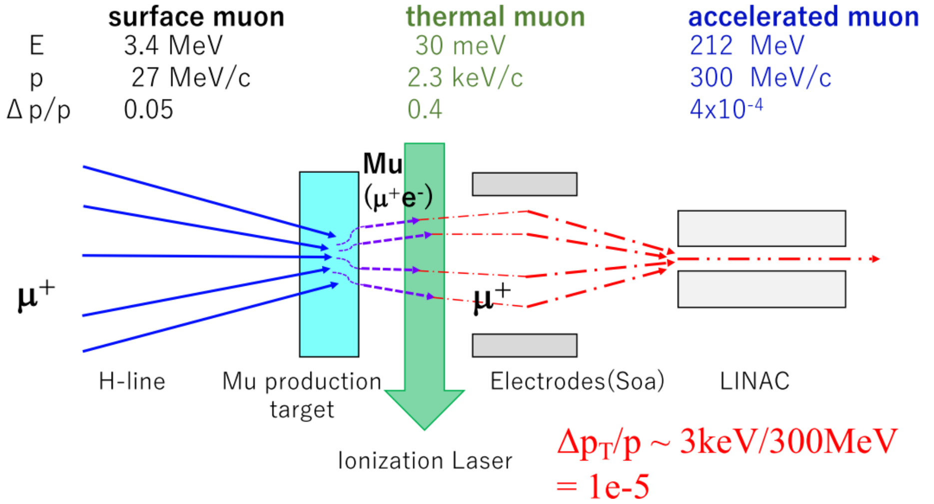
H-line experimental building

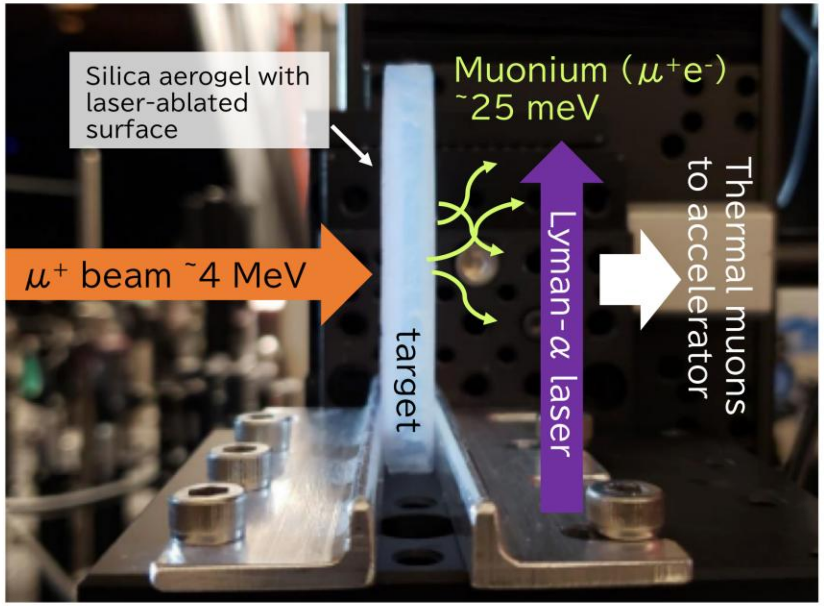




② Thermal Muon Production

- Surface muon stopped at a target and muonium emitted.
- A muonium is ionized by laser and thermal muon beam is produced.



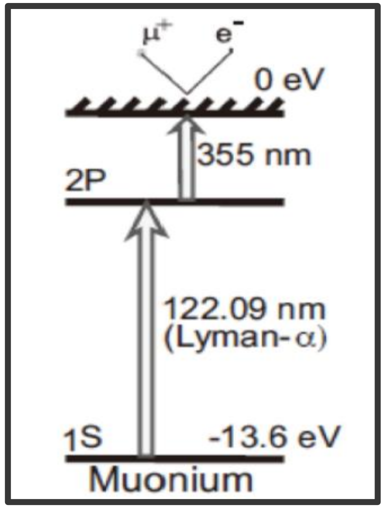


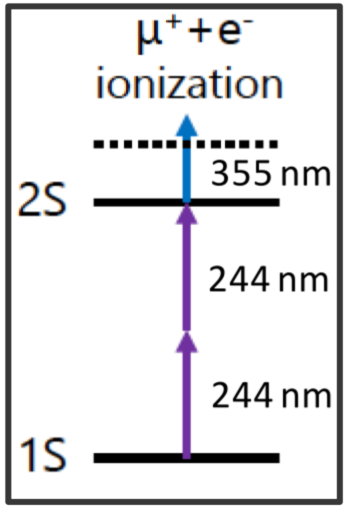
Muonium production target : Laser ablated silica aerogel

- ×10 more muonium emission rate compared to flat silica aerogel.

Laser-resonant ionization methods

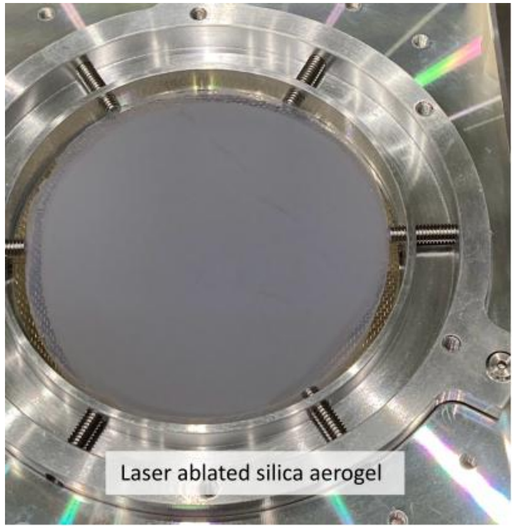
- Two scheme under consideration.
  - 1S-2P excitation by 122 nm(Lyman-α) laser
    or 1S-2S excitation by 244 nm laser

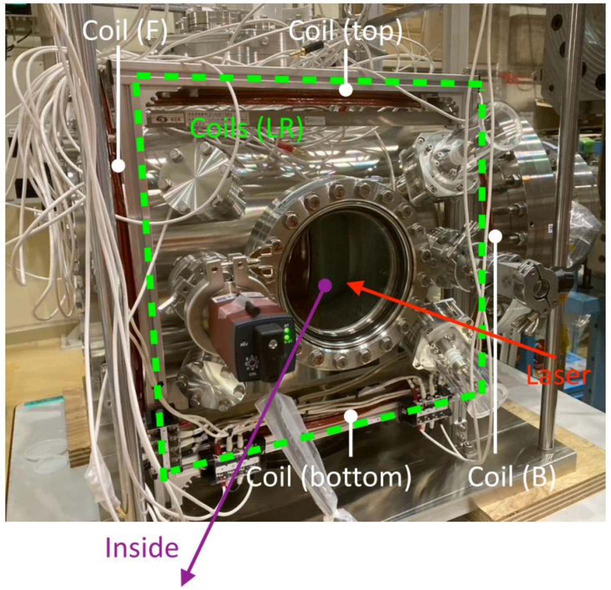


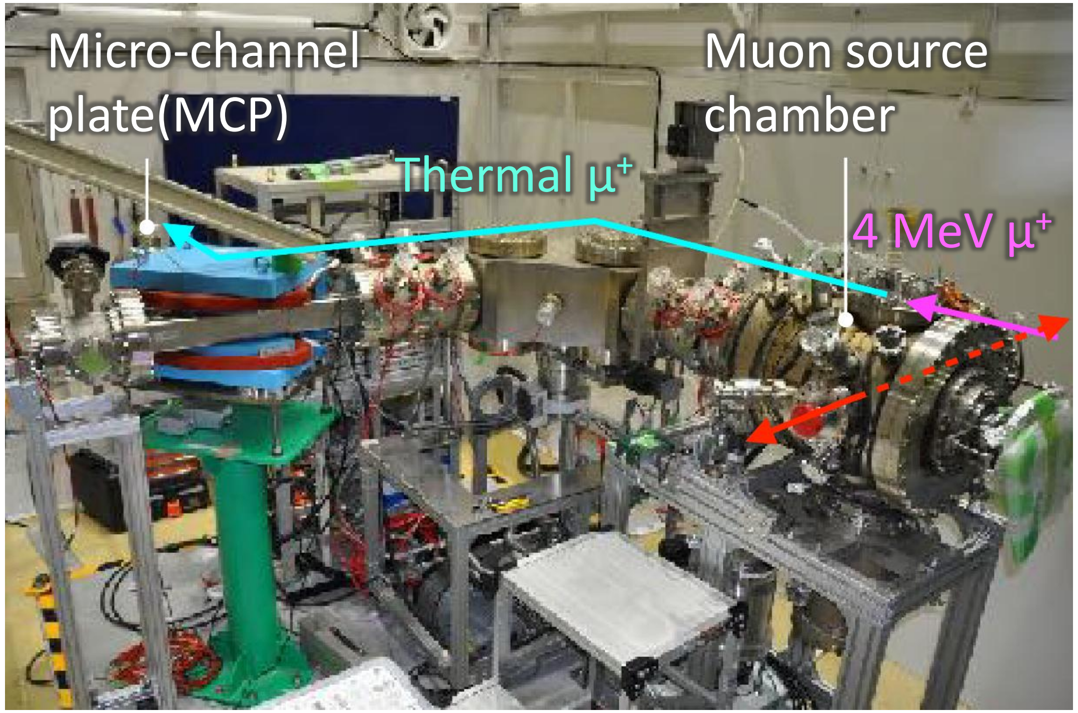


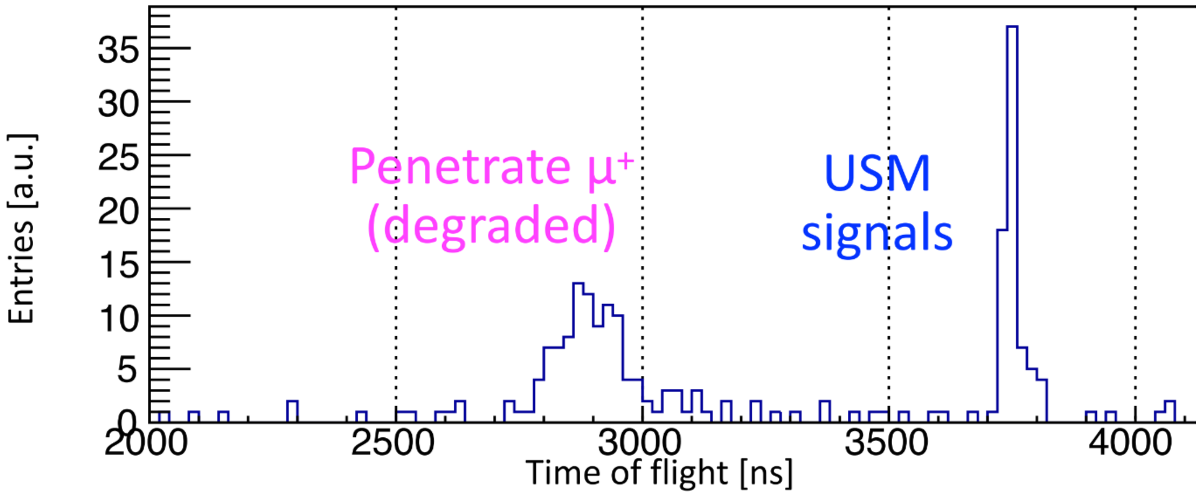
② Demonstration of Thermal Muon Production

- Demonstration of thermal muon production was started at S2 area (Feb. 2023~).
- Thermal muons have been successfully observed with real muon source chamber (Mar. 2024).



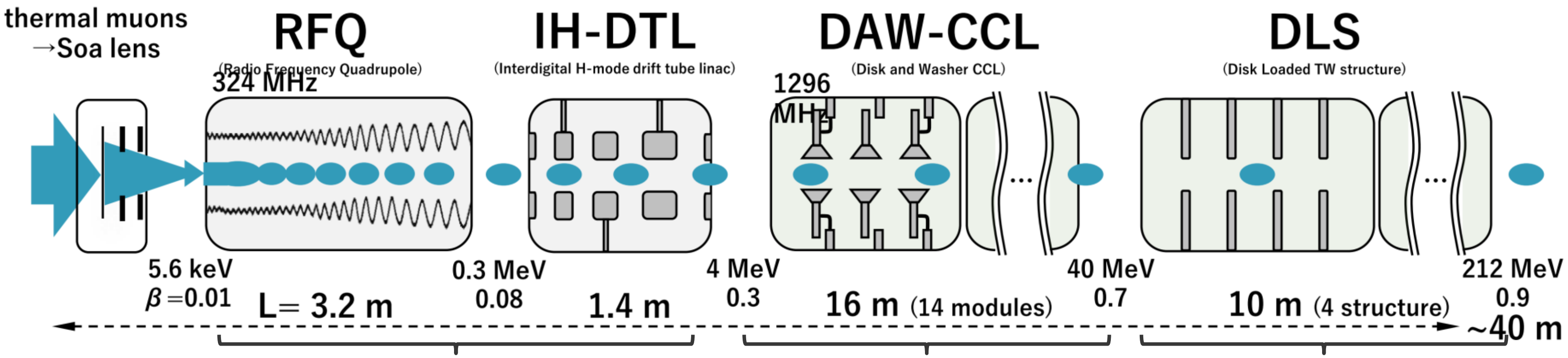






③ Muon Acceleration

- Thermal muons are reaccelerated up to p=300 MeV/c by muon LINAC.
  - Fast acceleration to avoid muon decay loss, No emittance growth.
- Different types of acceleration cavity to realize fast re-acceleration through wide β region.

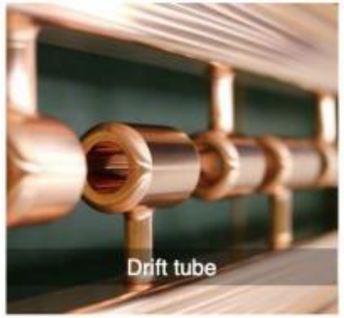


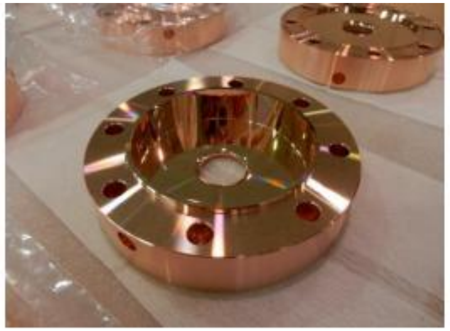
Ready

Ready : Acceleration Test in 2026/2027

Ready for production except for bridge coupler

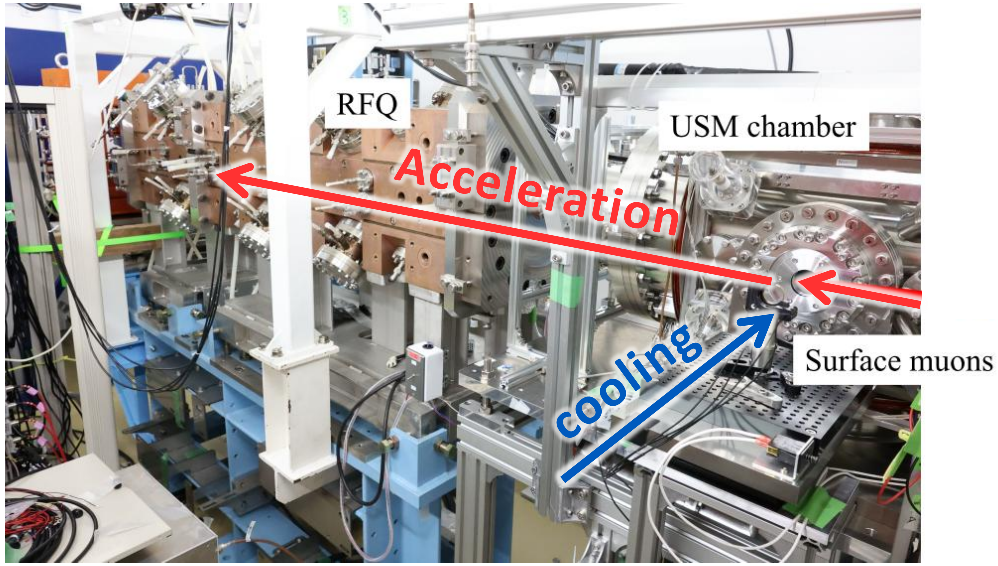
Ready for production except for pulse compressor

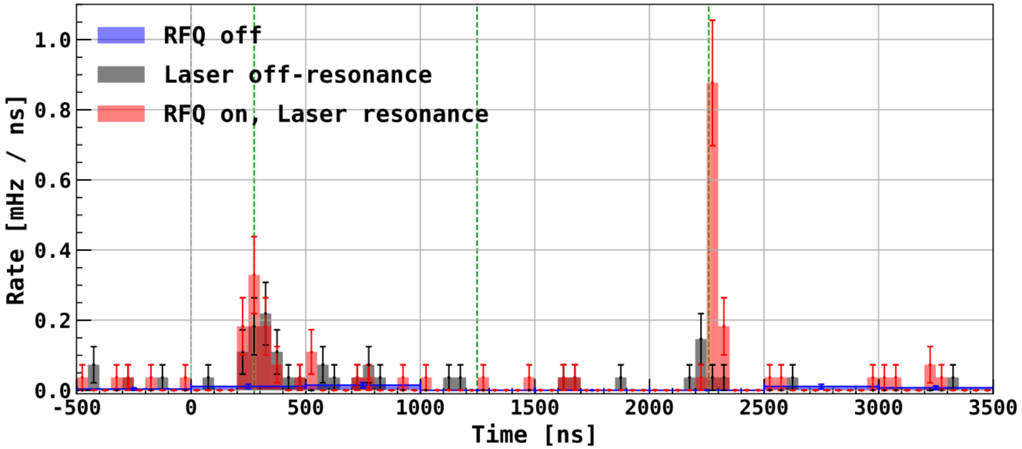


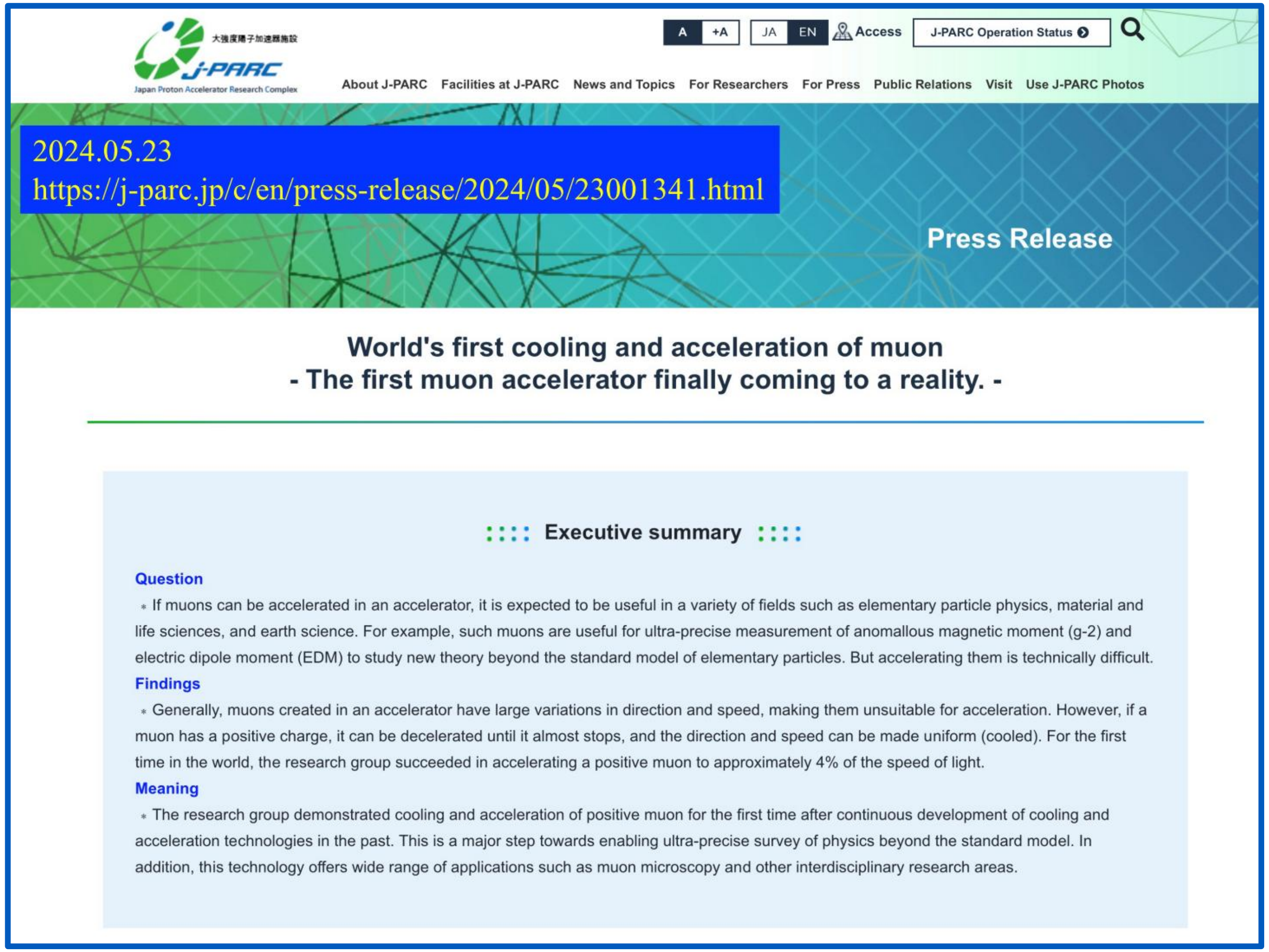


③ Demonstration of Muon Acceleration

- Acceleration of thermal muon to 90 keV was demonstrated using prototype RFQ in Apr. 2024.
- Paper are accepted for the publication in PRL *(arXiv:2410.11367)*.






2024.05.23
https://j-parc.jp/c/en/press-release/2024/05/23001341.html

Press Release

World's first cooling and acceleration of muon
- The first muon accelerator finally coming to a reality. -

Executive summary

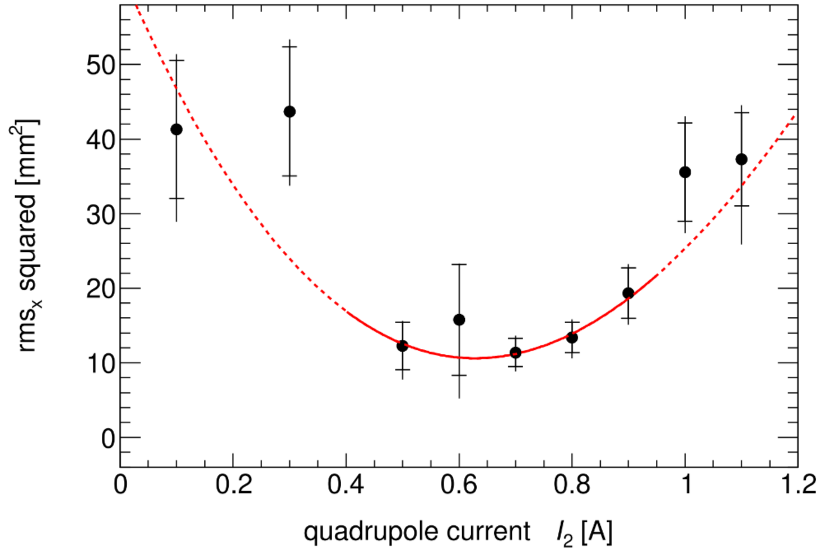
Question
- If muons can be accelerated in an accelerator, it is expected to be useful in a variety of fields such as elementary particle physics, material and life sciences, and earth science. For example, such muons are useful for ultra-precise measurement of anomallous magnetic moment (g-2) and electric dipole moment (EDM) to study new theory beyond the standard model of elementary particles. But accelerating them is technically difficult.

Findings
- Generally, muons created in an accelerator have large variations in direction and speed, making them unsuitable for acceleration. However, if a muon has a positive charge, it can be decelerated until it almost stops, and the direction and speed can be made uniform (cooled). For the first time in the world, the research group succeeded in accelerating a positive muon to approximately 4% of the speed of light.

Meaning
- The research group demonstrated cooling and acceleration of positive muon for the first time after continuous development of cooling and acceleration technologies in the past. This is a major step towards enabling ultra-precise survey of physics beyond the standard model. In addition, this technology offers wide range of applications such as muon microscopy and other interdisciplinary research areas.

③ Demonstration of Muon Cooling and Acceleration

- Transverse phase-space distribution of the beam was measured by “Q-scan”.
  - Strength of quadrupole field (=focal length) v.s. beam spot sizes
- Normalized emittance was reduced with more than two order.



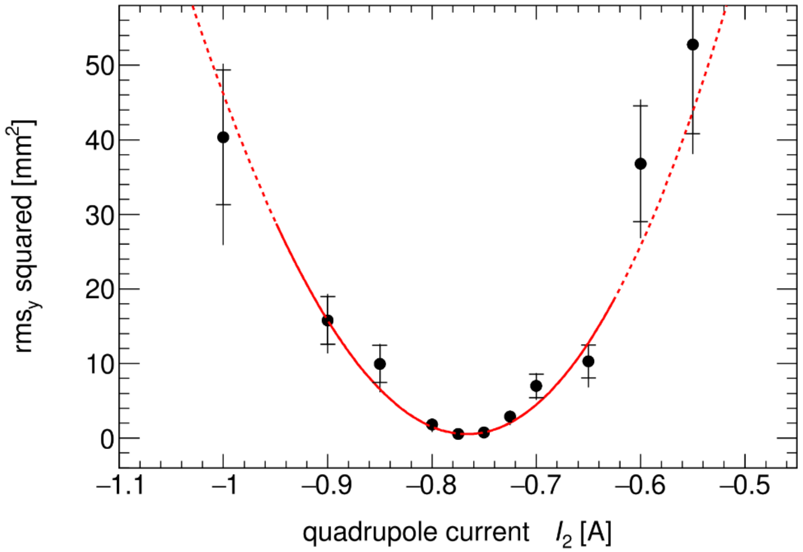
before cooling

ε_x = 170 π mm mrad

x 1/200

after cooling + acceleration

$\varepsilon_x = 0.85 \pm 0.25^{+0.22}_{-0.13}$ π mm mrad



before cooling

ε_y = 130 π mm mrad

x 1/400

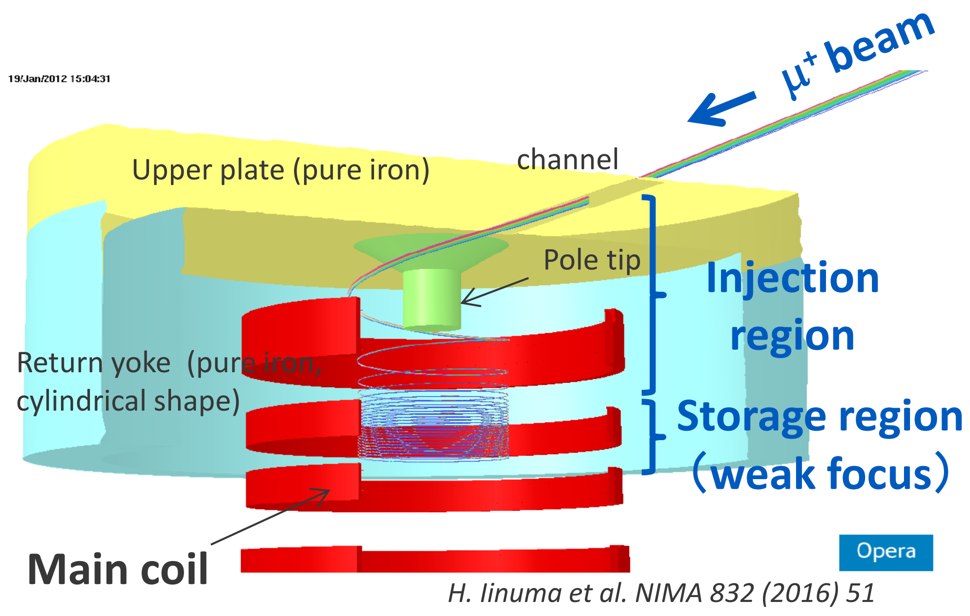
after cooling + acceleration

$\varepsilon_y = 0.23 \pm 0.03^{+0.05}_{-0.02}$ π mm mrad

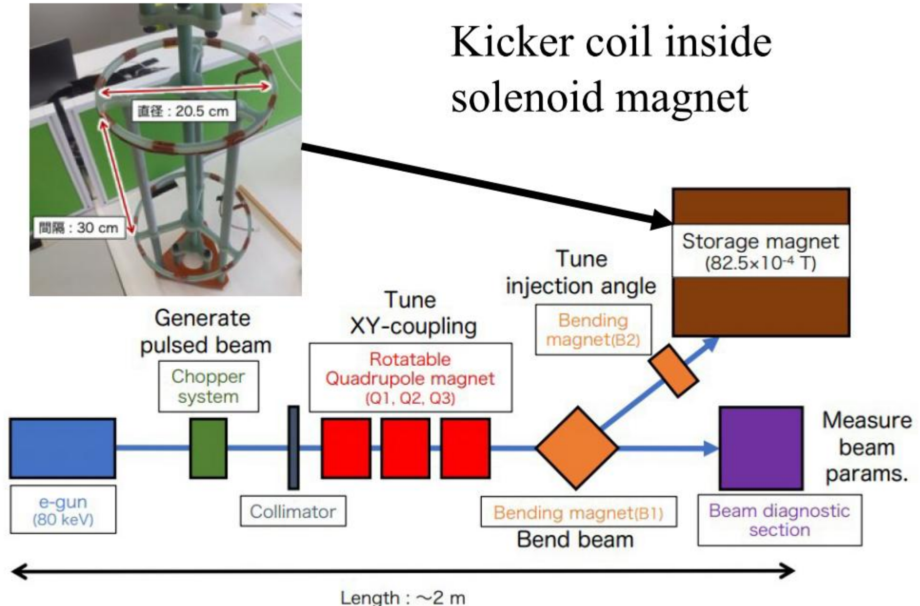
- Acceleration up to 4 MeV at H2 area is in planned for 2027.

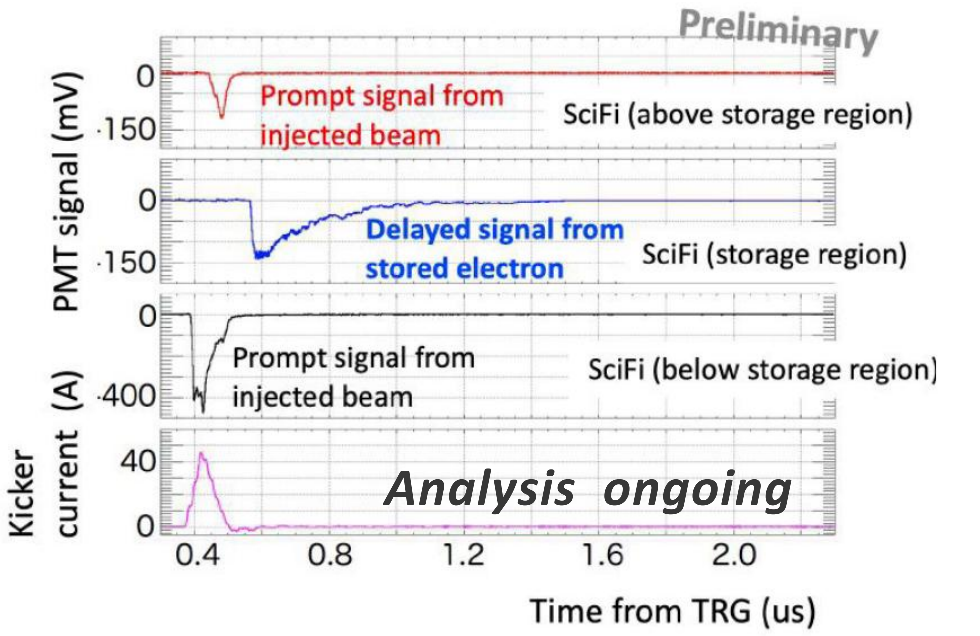
④ 3D-Spiral Beam Injection

- For injection of muon beam into compact storage ring, **3D-spiral injection scheme** has been invented.
- Demonstration of the 3D-spiral injection scheme is ongoing with electron beam.
- First signal from stored electron beam is successfully observed.



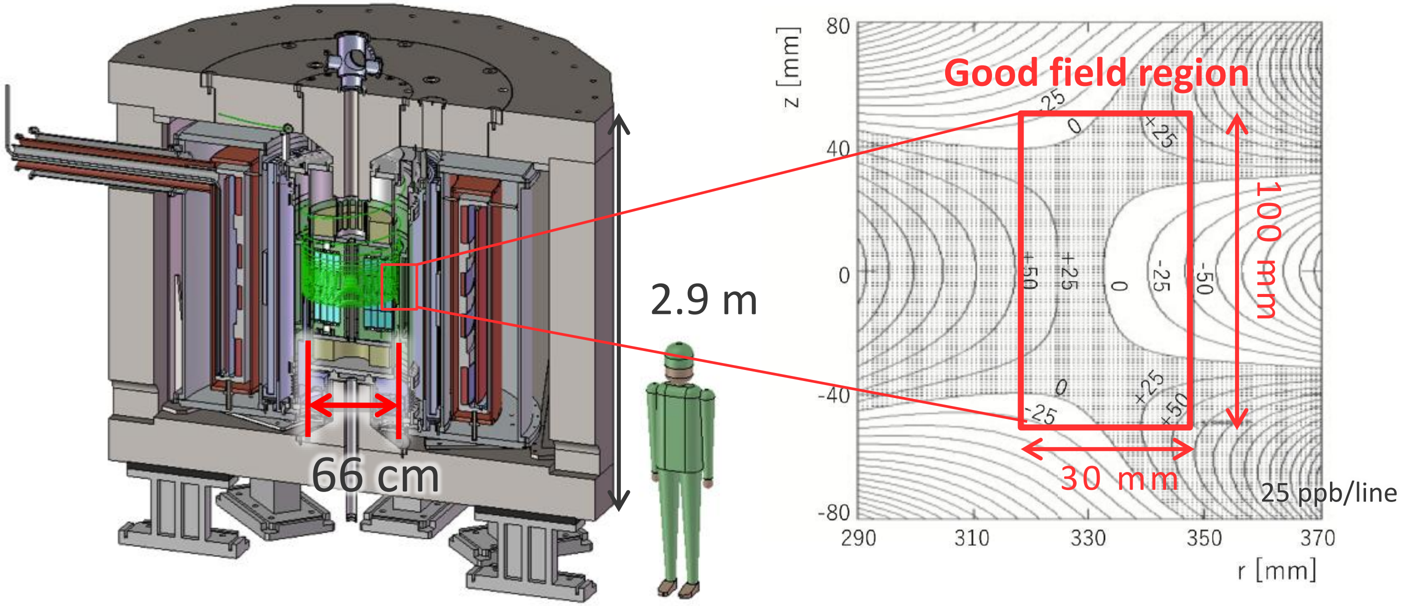
H. Iinuma et al. NIMA 832 (2016) 51





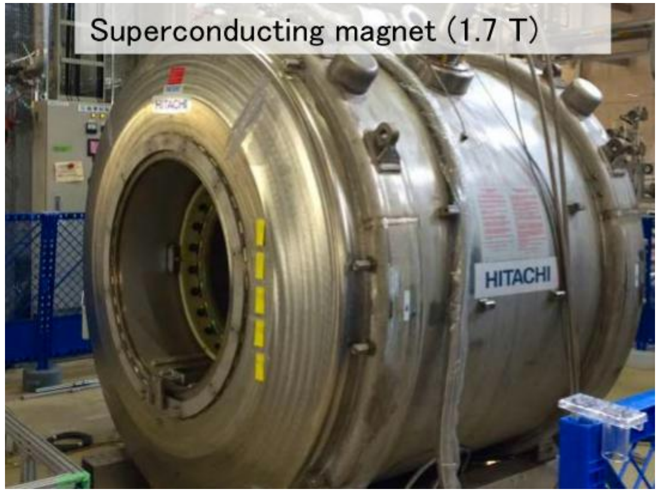
⑤ Muon Storage Magnet

- A compact MRI-type superconducting solenoid magnet is used to store a muon beam.
  - B = 3 T, ϕ = 66 cm
- High uniformity of the magnetic field is achieved by shimming.
- Local uniformity of 1 ppm was demonstrated with the magnet used in the MuSEUM experiment.

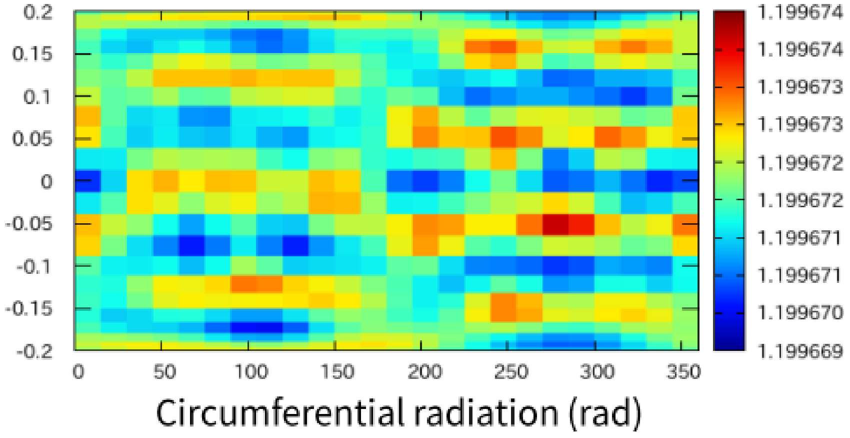


M. Abe et. Al., Nuclear Inst. and Methods in Physics Research A890, 51 (2018)

MuSEUM magnet



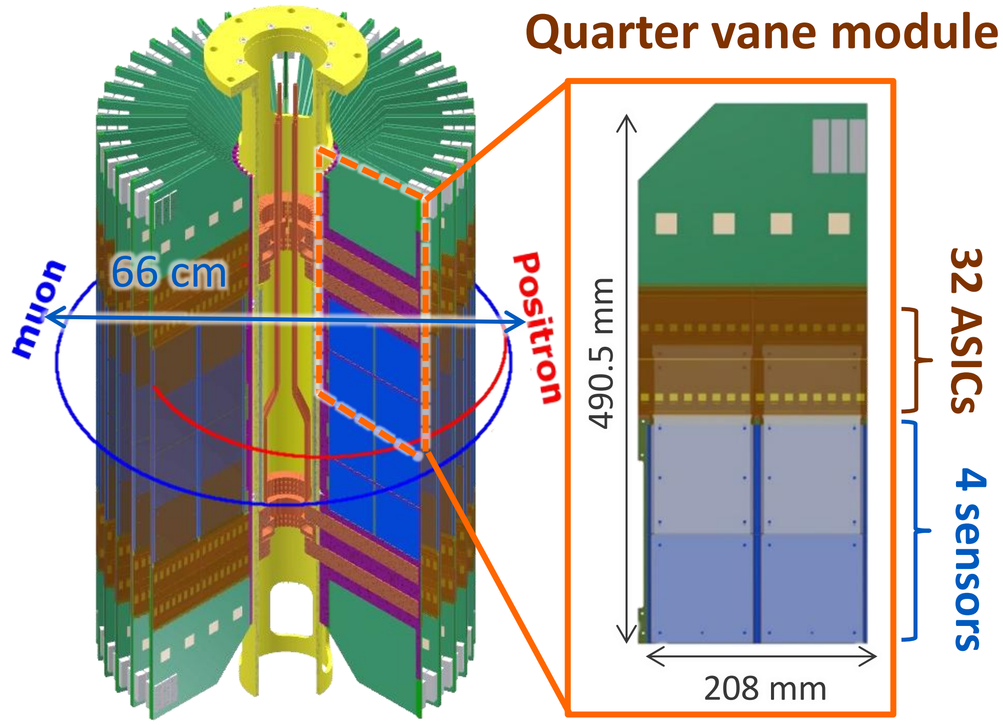
After shimming with Fe, Ni, Putty (0.17 ppm_{pp})



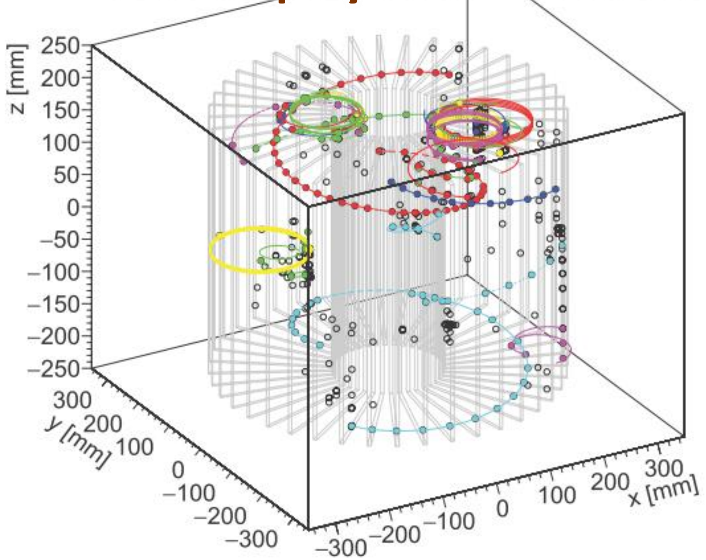
⑥ Positron Detector

- Positron tracks are measured by **Silicon-strip detector**.
  - Positrons with a momentum of 100-300 MeV/c
  - High hit rate capability (6 tracks/ns) and stability over early to late rate changes (1.4 MHz → 10 kHz)
  - Design optimized for pulsed beam.

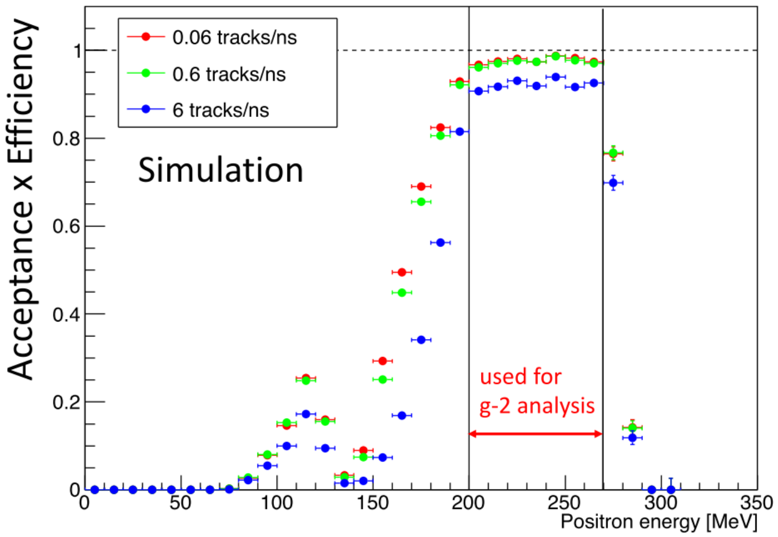
Quarter vane module



Event display with 25 muons

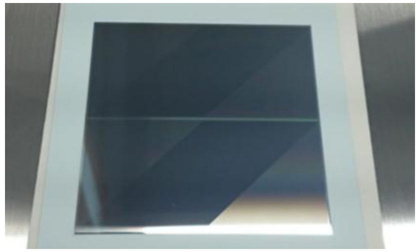


Reconstruction efficiency



⑥ Positron Detector

- Major components are in or completed the mass-productions.
- Prototype module “quarter-vane” is assembled.
- Various operation test are also performed using the prototype module.



Rigid printed circuit boards

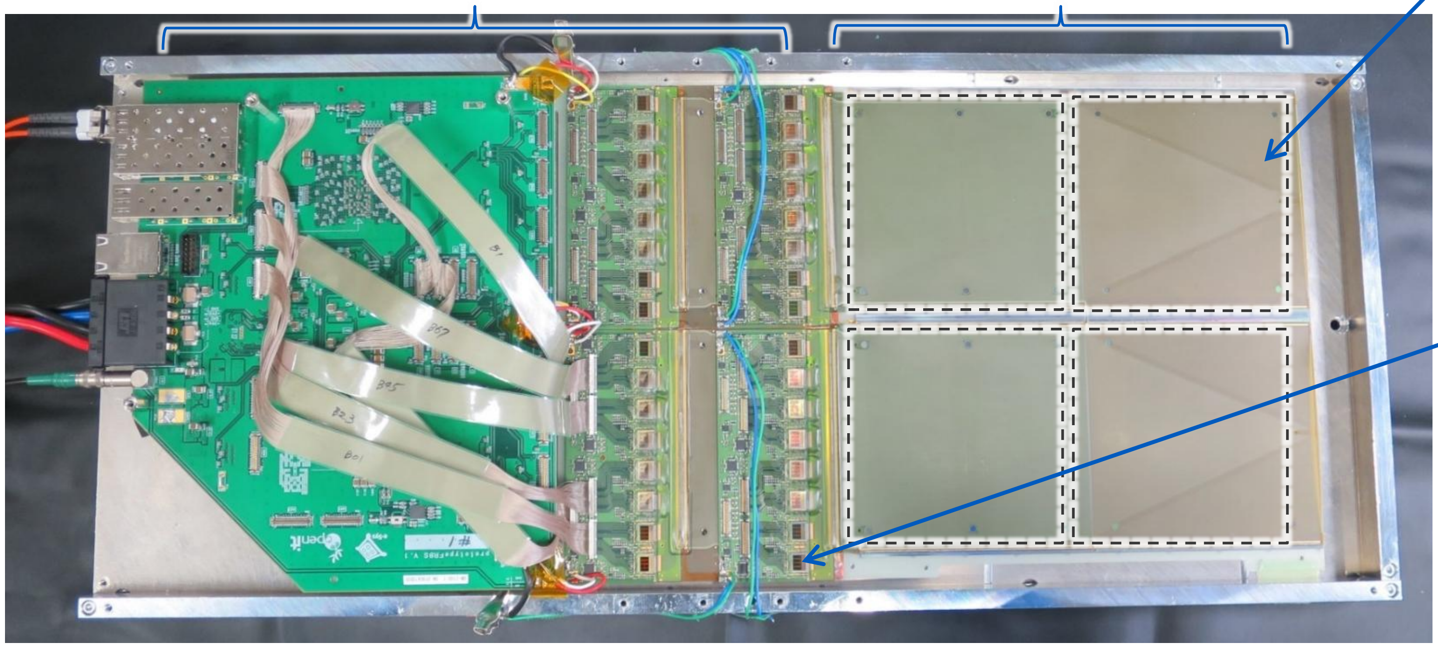
- Prototypes were fabricated and being tested.

Flexible printed circuit boards

- Made by Fujikura Ltd.
- Mass-production : done

Silicon-strip sensor

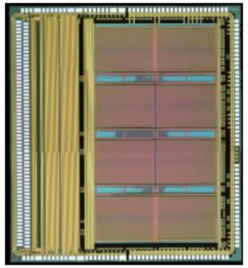
- Made by Hamamatsu Photonics K.K., S13804
- Strip pitch : 190 μm
- Mass-production : ongoing



Quarter vane module

Readout ASIC (SliT)

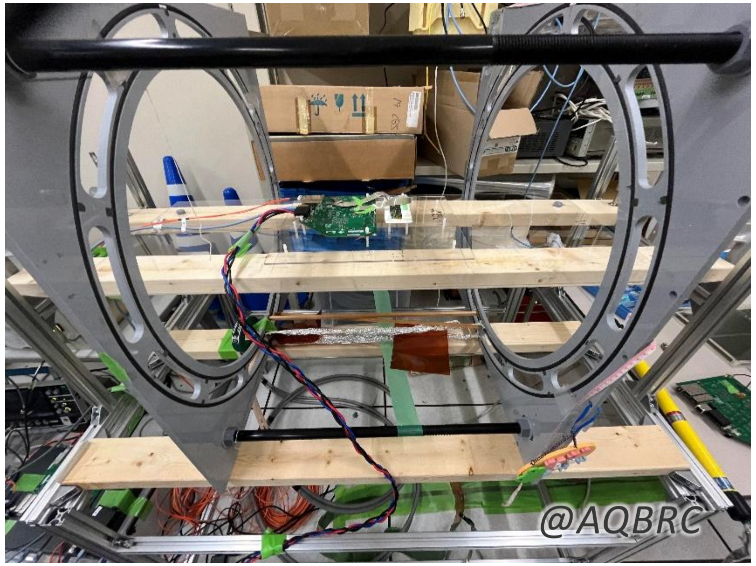
- Silterra 180-nm CMOS process
- Binary output with sampling interval of 5 ns
- Mass-production and QA : done



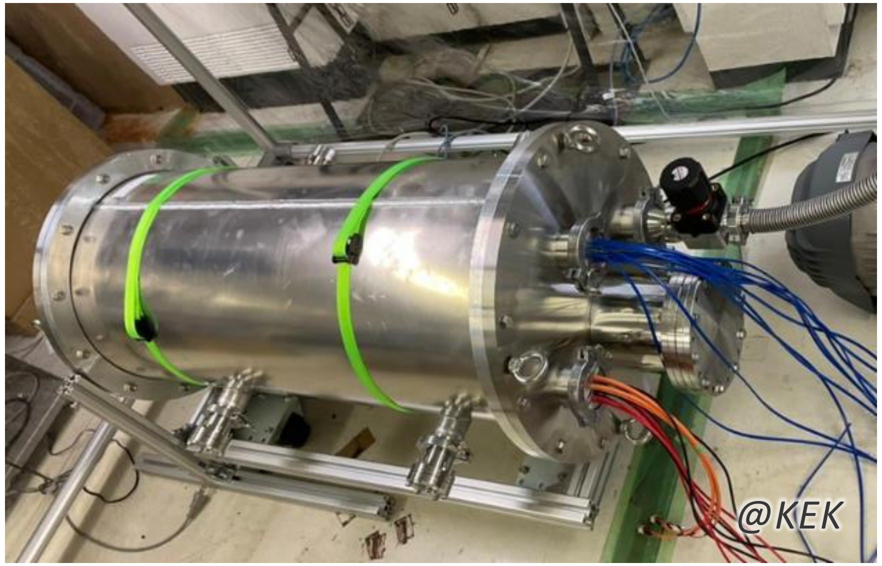
⑥ Positron Detector

- Major components are in or completed the mass-productions.
- Prototype module “quarter-vane” is assembled.
- **Various operation test are also performed using the prototype module.**

Operation test
in static magnetic field



Operation test
in kicker magnetic field

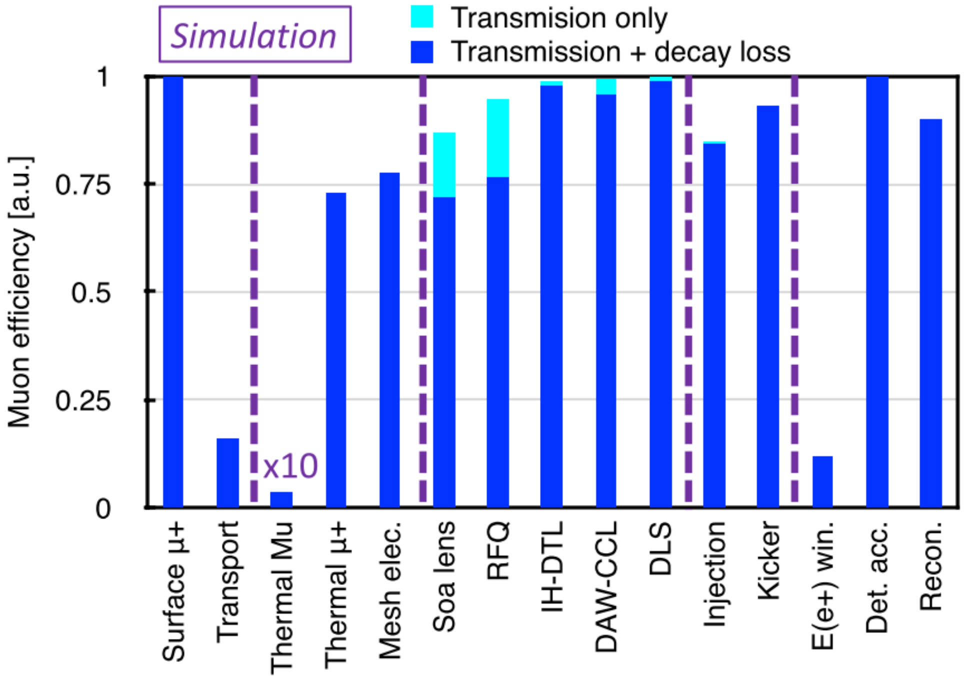


Cooling test (in preparation)

Expected Sensitivities

- Overall efficiency : 1.3×10^{-5}
- Assuming 2.2×10^{7} sec (~255 days) of data taking, total number of reconstructed e^{+} is 5.7×10^{11}.

Prog. Theor. Exp. Phys. 2019, 053C02



Expected uncertainties

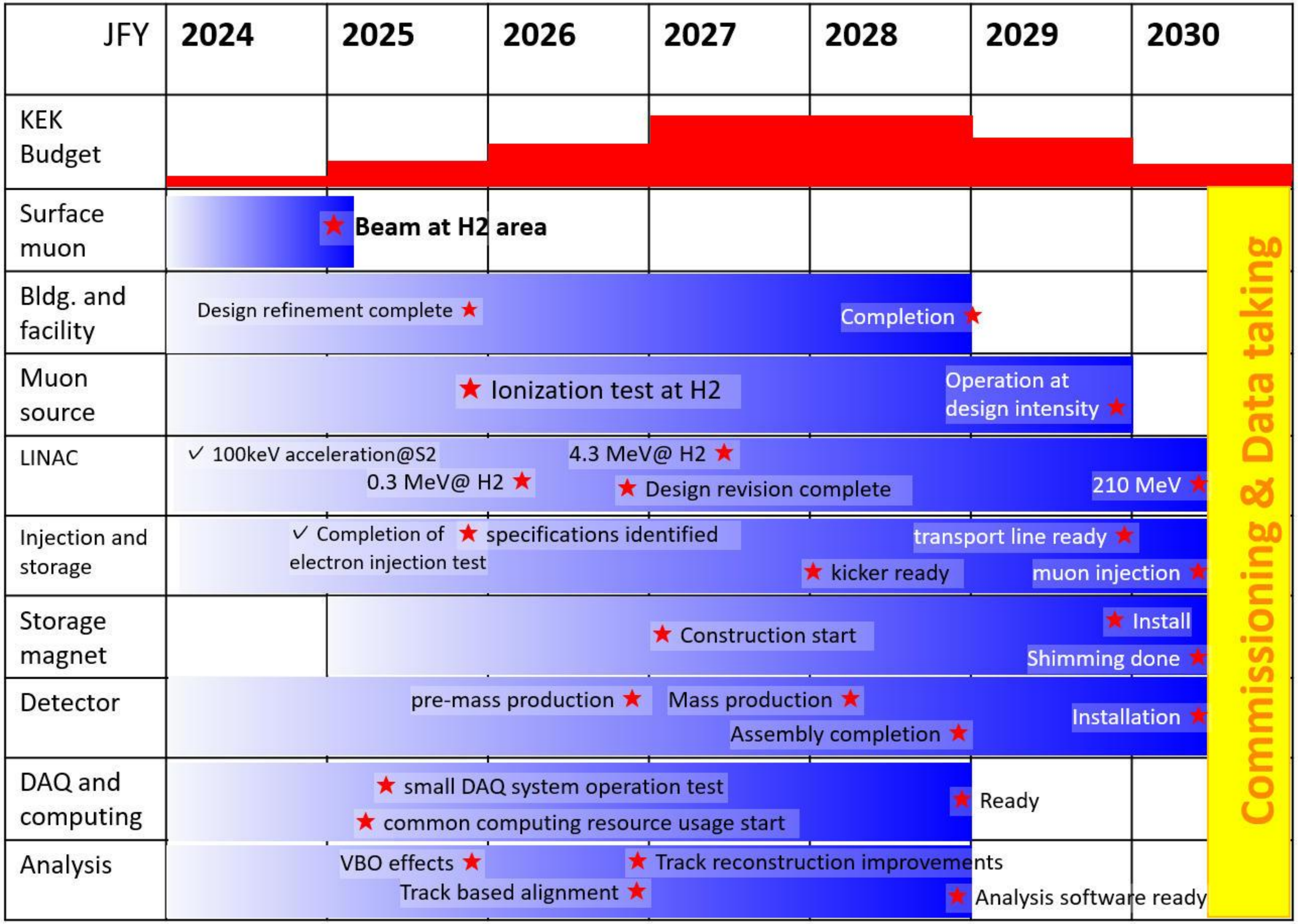
	Stat.	Syst.
$\delta\, a_{\mu}$ [ppb]	450	<70
δ EDM [10^{-21} e・cm]	1.5	0.36

Anomalous spin precession (ω_a)		Magnetic field (ω_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
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

- **2-year running will reach the BNL precision of a_{μ}.**
- **Systematic uncertainties will be much smaller than the statistical ones.**

Schedule and Milestones

Updated, April 2, 2025



J-PARC Muon g-2/EDM Collaboration

Tamaki Yoshioka (Kyushu)

Collaboration board (CB)
Chair: T. Yoshioka

Executive board (EB)
Spokesperson: T. Mibe

2024.3 Shanghai Jiao Tong University
2024.6 Iwate University
2025.3 University of Liverpool

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

Subgroups

- **Surface muon beam** — leader: T. Yamazaki, N. Kawamura
- **Ultra-slow muon** — leader: K. Ishida
- **LINAC** — leader: M. Otani
- **Injection and storage** — leader: H. Iinuma
- **Storage magnet, field measurements** — leader: K. Sasaki
- **Detector** — leader: T. Yoshioka
- **DAQ and computing** — leader: Y. Sato
- **Analysis** — leader: T. Yamanaka

Interface coordinators

K. Ishida, M. Otani, Y. Kondo, H. Iinuma, T. Kume, Y. Sato, T. Suehara, T. Yamanaka

Committees

Speakers committee
chair: K.Ishida, **Y. Sato**

Publication committee
chair: B. Shwartz

Working groups

physics analysis
T. Yamanaka, S. Ogawa

Domestic institutes：
Kyushu, Nagoya, Tohoku, Niigata, Toyama C, Tokyo, Ibaraki, RIKEN, JAEA, Iwate, etc.
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

The 29th collaboration meeting at J-PARC, Dec. 11-13, 2024

Summary

- **J-PARC muon g-2/EDM experiment** aims to measure muon g-2 and EDM with a method different from BNL/FNAL experiment.
  - Re-accelerated thermal muon beam with no strong focusing.
  - Compact MRI-type storage ring with a good injection efficiency and high uniformity of local B-field.
  - Full-tracking detector with large acceptance
- The experiment is getting ready for realization.
  - World's first muon cooling and acceleration was successfully demonstrated.
  - First beam to H2 was delivered and acceleration up to 4 MeV is in planned for 2027
- Expecting data taking from FY2030.
  - Intending to reach the BNL precision in ~2 year running.

Backup