Muon g-2/EDM Experiment at J-PARC

Yusuke Takeuchi (Kyushu University)
for the J-PARC muon g-2/EDM collaboration

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the 24th International Spin Symposium

Muon g-2 and EDM

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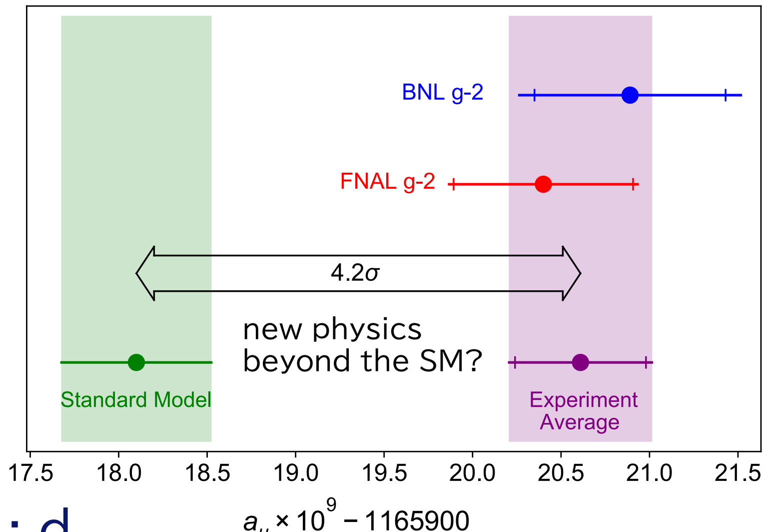
- One of the best probes for New Physics (NP) beyond the SM.
- Anomalous magnetic moment (g-2) of muon : a_μ
  - Calculated in 0.37 ppm precision in the SM.
  - (Phys. Rep. 887 (2020) 1–166)
  - The best experimental precision is 0.46 ppm by the FNAL E989 Experiment.
  - The experimental average value deviates from the SM prediction by 4.2 σ.
  - This deviation may be the result of physics beyond the SM.

Phys. Rev. Lett. 126, 141801 (2021)



- Electric dipole moment (EDM) of muon : d_μ
  - If non-zero EDM exists, it means T-violation.
  - Current experimental limit for muon is $|d_\mu| < 1.8\times10^{-19}$ e·cm by the BNL E821 experiment.
  - (Phys. Rev. D 80, 052008 (2009))
  - The SM expectation of muon EDM is ~2×10^{-38} e·cm.
  - Some theoretical models beyond the SM predict much larger values, current experimental technique would reach that values.

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

$$a_\mu = \frac{g-2}{2}$$

$$\vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}$$

g: the Landé g-factor
η : a corresponding factor for the EDM

Experimental approach

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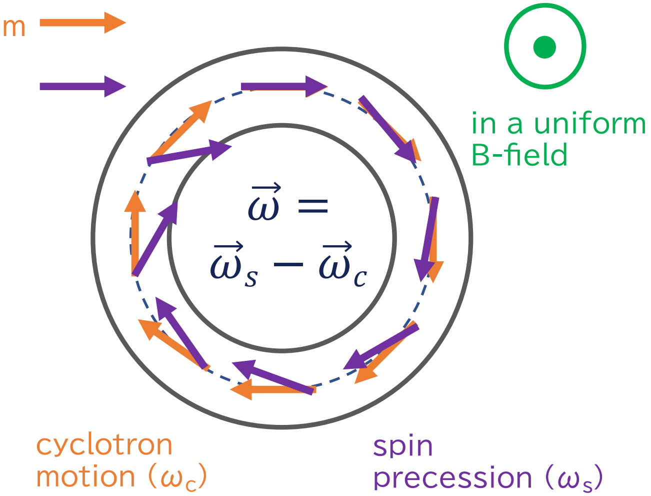
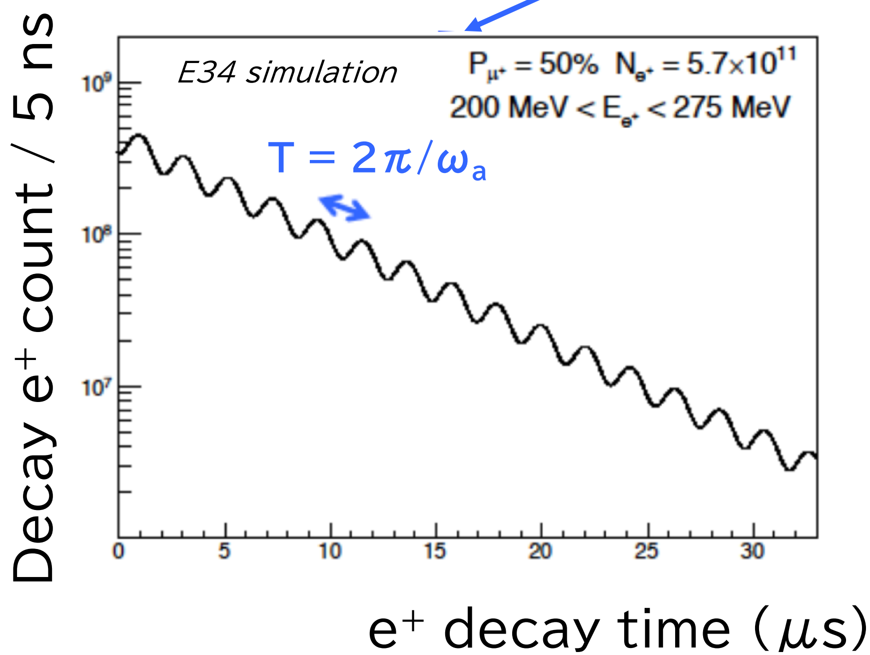
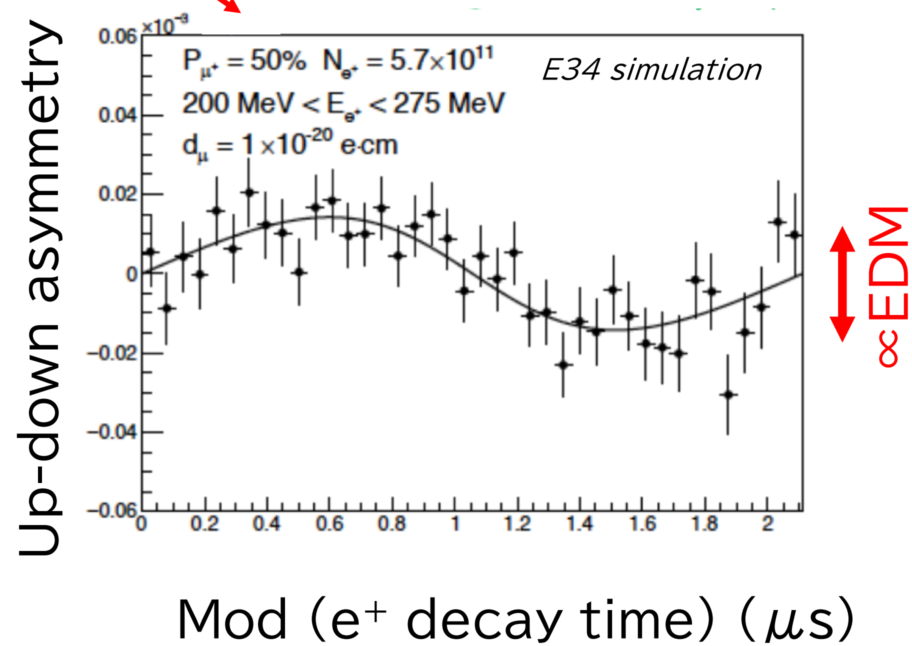
- Measure the spin precession frequency to extract a_μ and η.

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m_\mu}\Bigg[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\omega_a} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} - \frac{\vec{E}}{c}\right)}_{\omega_\eta}\Bigg]$$







Experimental approach

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- Eliminate the $\beta \times E$ term for simplification.

⇨ "Magic momentum" p = 3.09 GeV/c

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

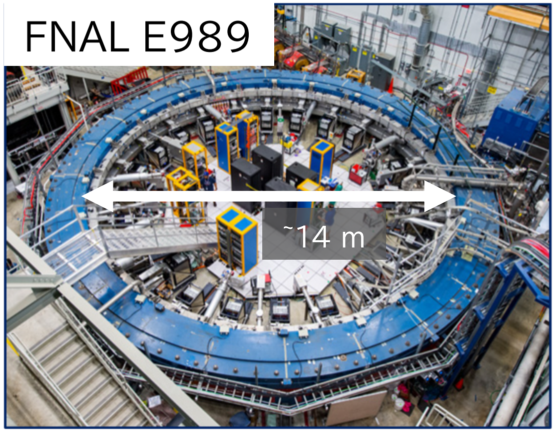
$$= -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{=0}\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} - \frac{\vec{E}}{c}\right)\right]$$

BNL/FNAL
γ = 29.3

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

FNAL E989

FNAL E989



p= 3.09 GeV/c , B=1.45 T
electric focusing

- In the BNL and FNAL experiments, to use a beam focusing electric field, the muon momentum is chosen to satisfy $\left(a_\mu - \frac{1}{\gamma^2-1}\right) = 0$.

Experimental approach

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- Eliminate the $\beta\times$E term for simplification.

➾ E = 0 with low-emittance muon beam

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

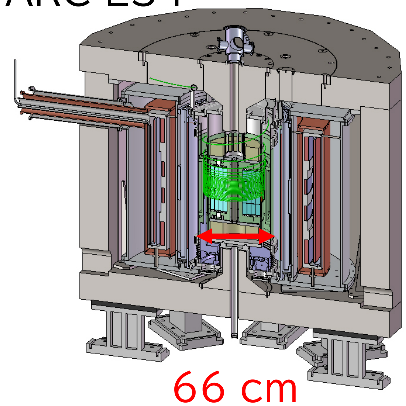
$$= -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\overset{=0}{\vec{\beta}\times\vec{E}}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} - \frac{\overset{=0}{\vec{E}}}{c}\right)\right]$$

J-PARC
E = 0 at any γ

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

J-PARC E34

J-PARC E34



p= 300 MeV/c , B=3 T
no electric field

- In the J-PARC experiment, the electric field itself is eliminated, $E = 0$.
- Use of a reaccelerated thermal muon beam is a key of this method.

J-PARC Facility

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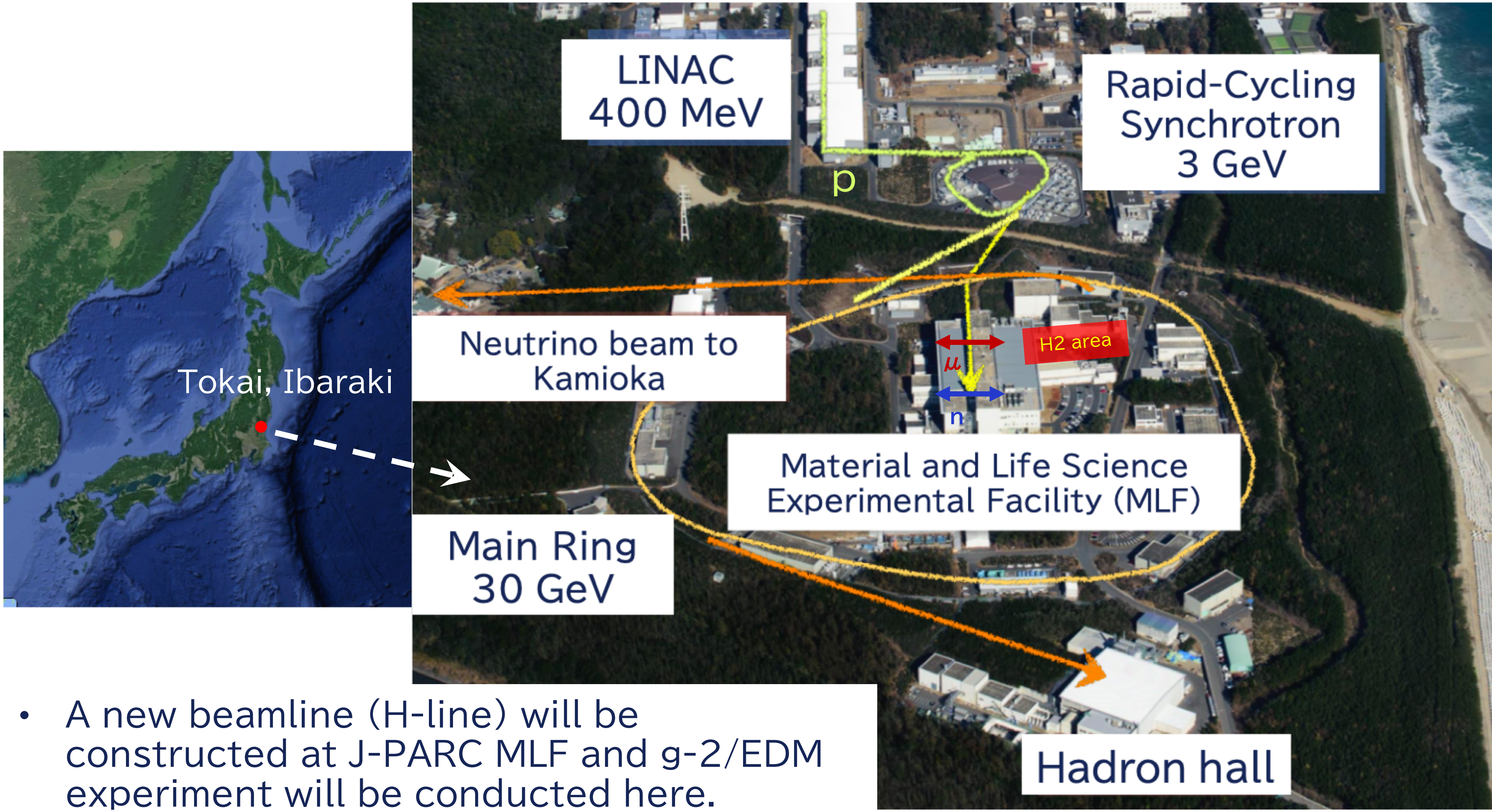
- Japan Proton Accelerator Research Complex (J-PARC)



- A new beamline (H-line) will be constructed at J-PARC MLF and g-2/EDM experiment will be conducted here.

J-PARC muon g-2/EDM experiment

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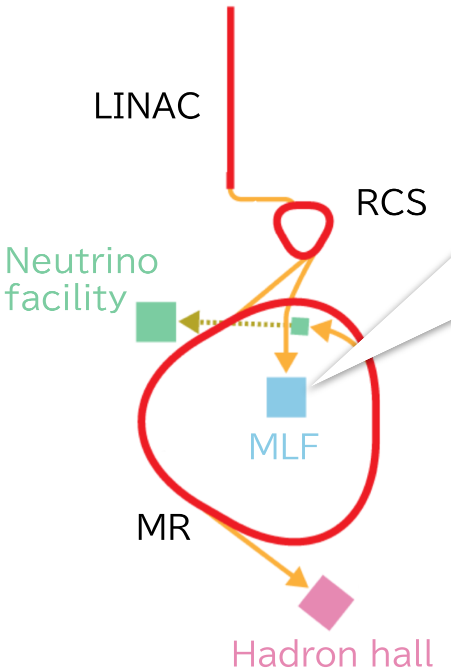

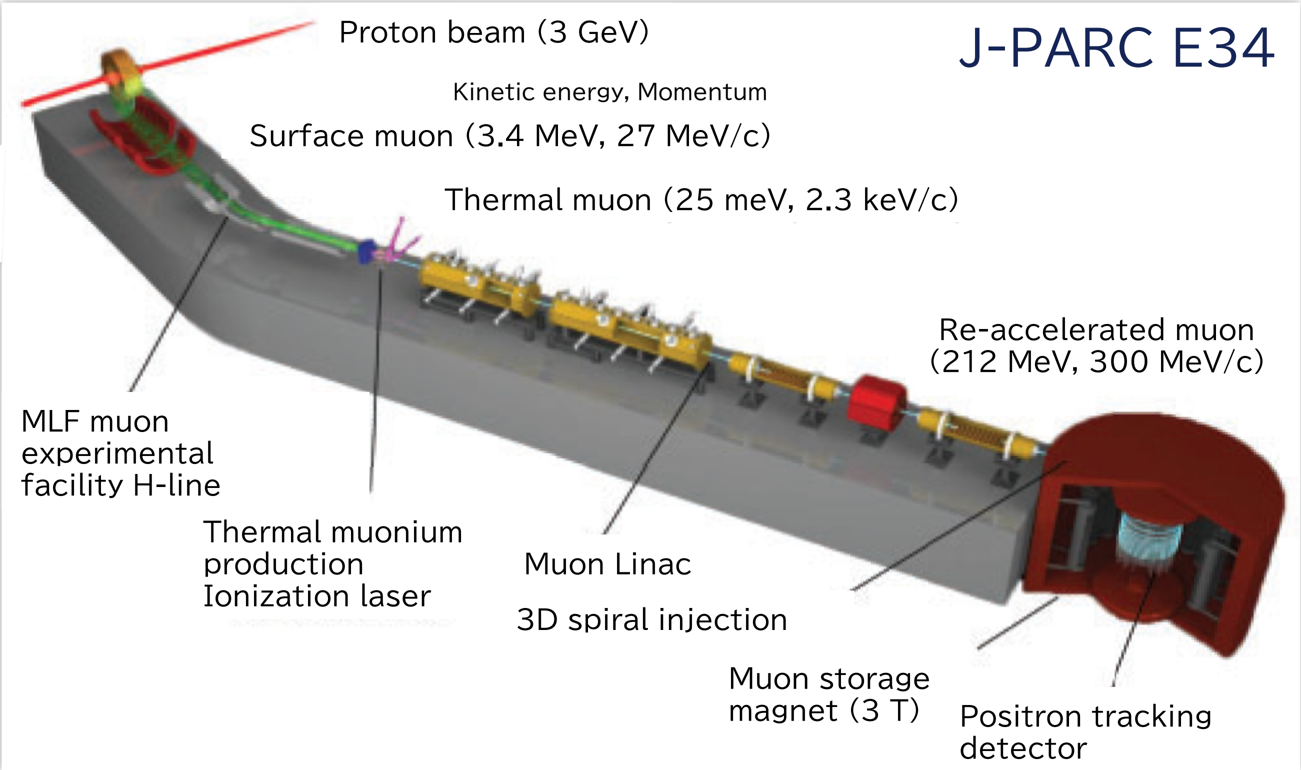

Features:

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

Completely different from BNL/FNAL method

Muon beamline (H-line)

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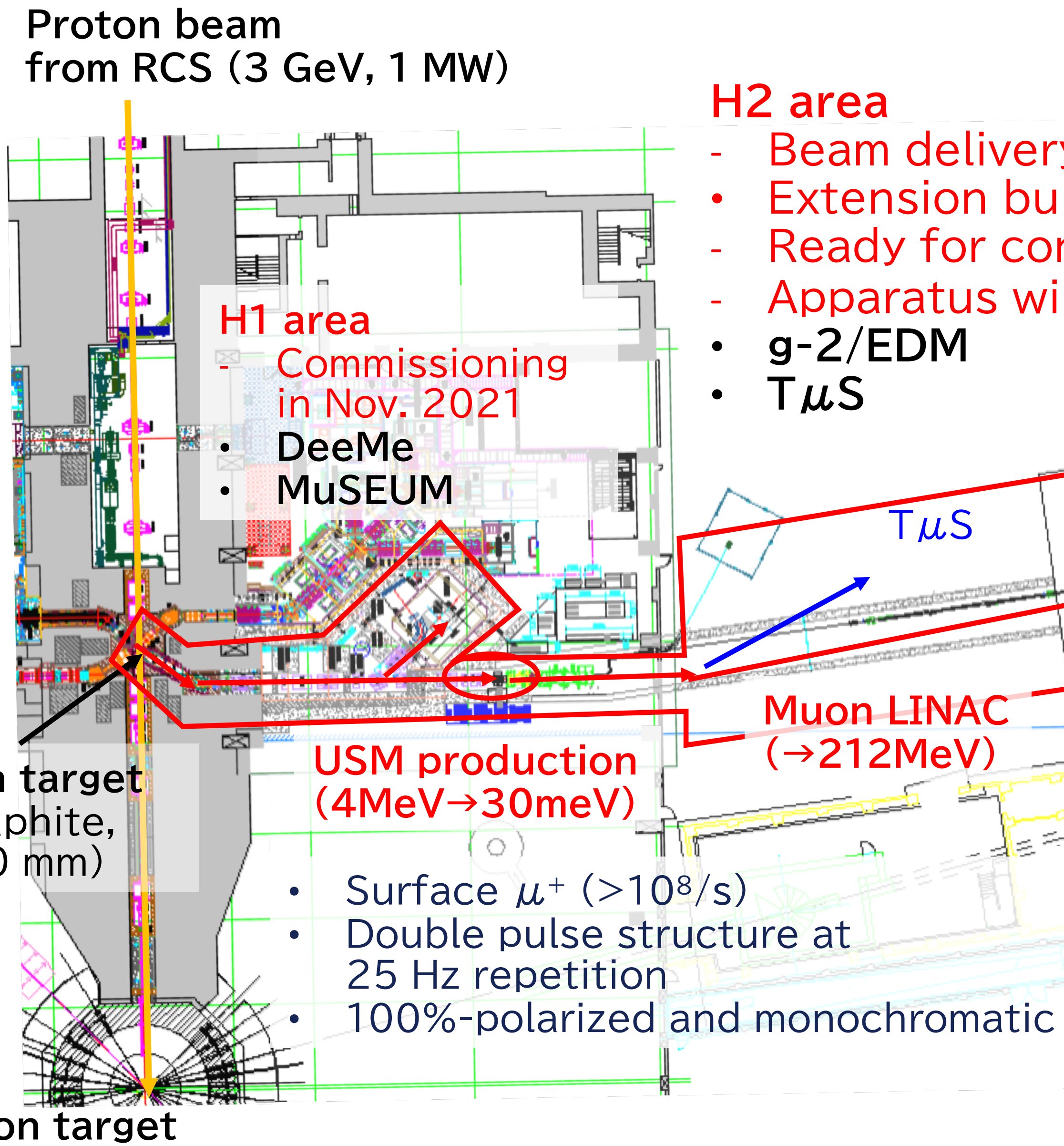
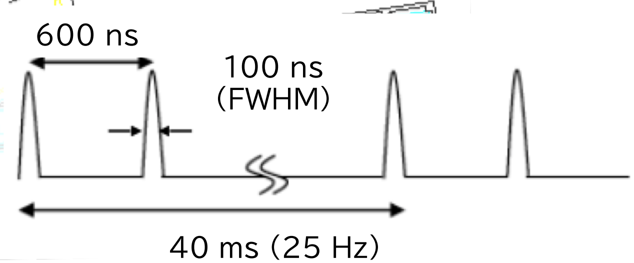
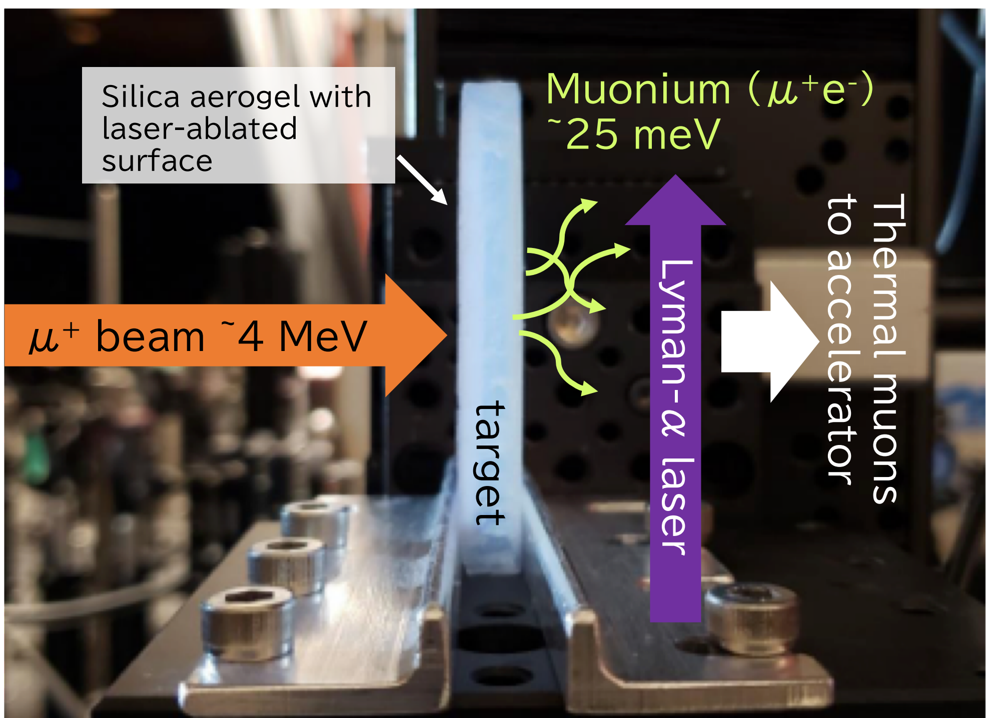


- Surface μ^+ ($>10^8$/s)
- Double pulse structure at 25 Hz repetition
- 100%-polarized and monochromatic

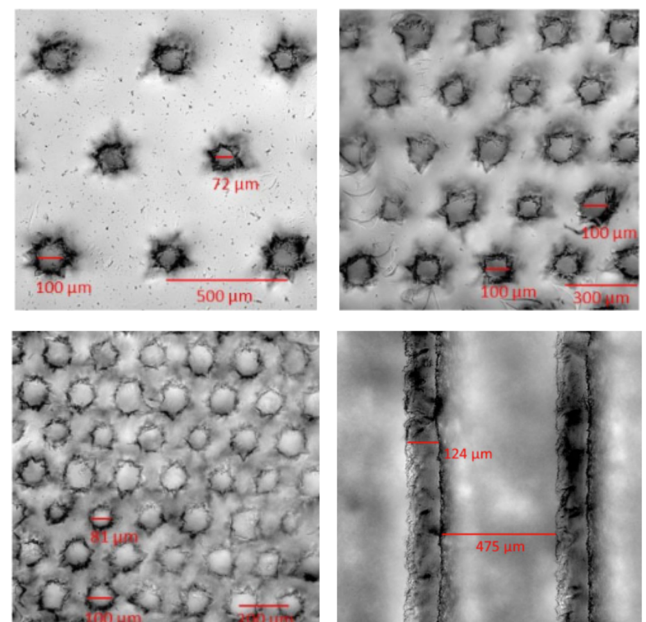


Thermal muon production

- Surface muon beam is stopped at a target and muonium (bound state of μ^+ and e^-) is produced.
- Laser-ablated silica aerogel is used for muonium production target.
- An electron is stripped from a muonium by intense laser and thermal muon beam is produced.



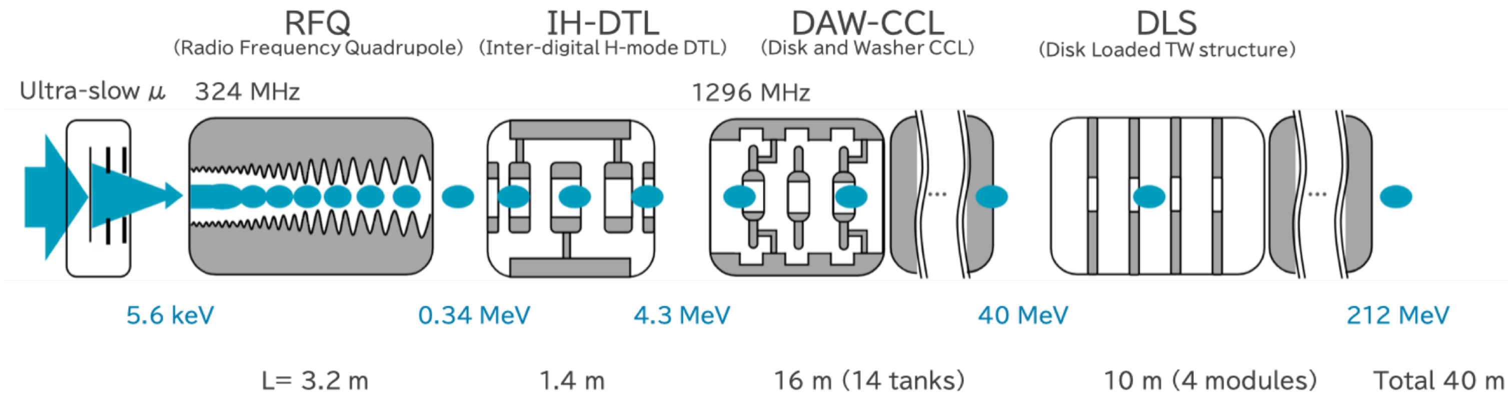
- Various laser-ablated structures and aerogel materials were studied.



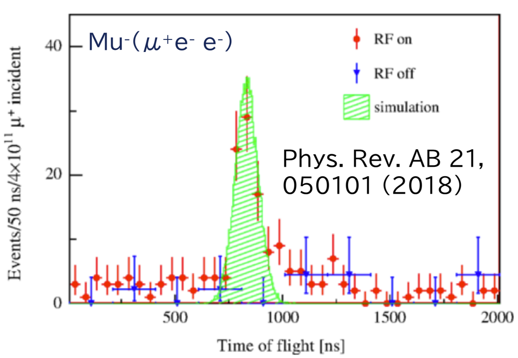
PTEP2020, 123C01

Muon acceleration

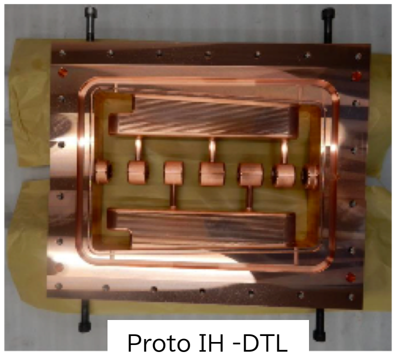
- Thermal muon is accelerated up to p=300 MeV/c in LINAC.



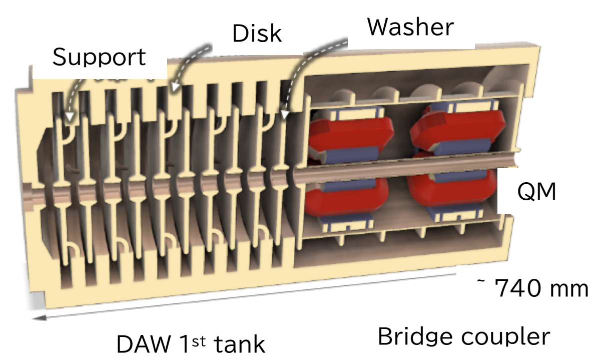
- The World's 1st acceleration of μ (in Mu^-) by RFQ in 2018.
- Acceleration of thermal μ using RFQ in 2022.



- The prototype of IH-DTL is being tested.
- Real one: to be fabricated in FY2021.



- The 1st tank of DAW-CCL: to be fabricated in 2021 FY.
- Finalizing design of DLS in FY2021.

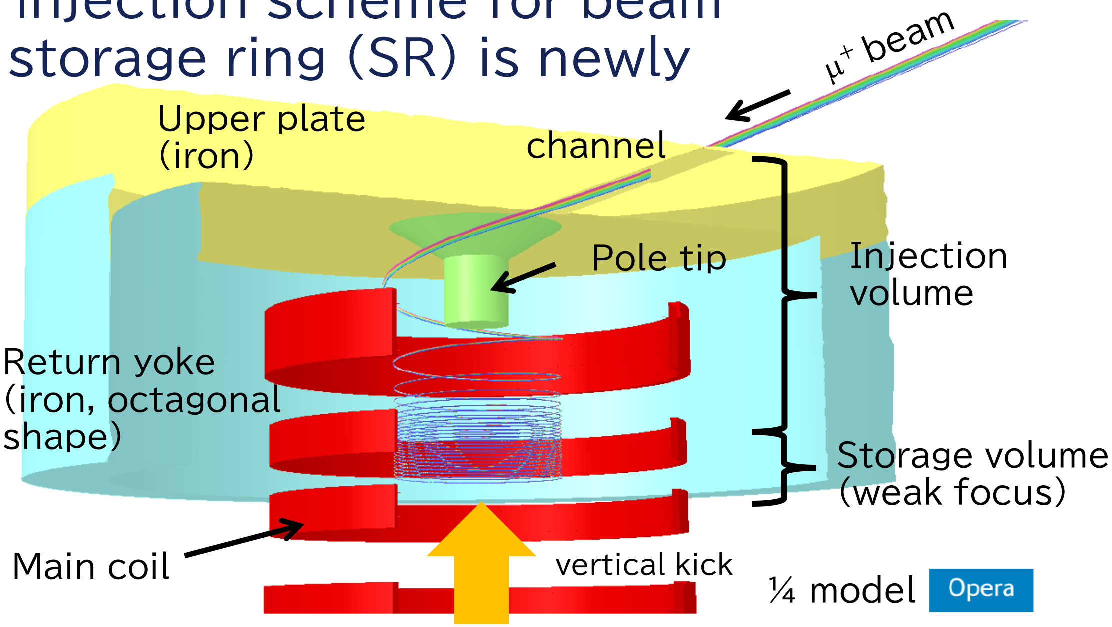


Injection

- A three-dimensional spiral injection scheme for beam insertion into a solenoidal storage ring (SR) is newly developed.

- 2D injection is quite difficult for our SR.
- Required kick is too fast and big due to its compactness.

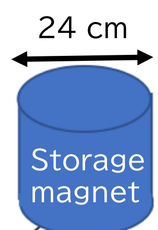
⇨ A 3D injection scheme is needed.

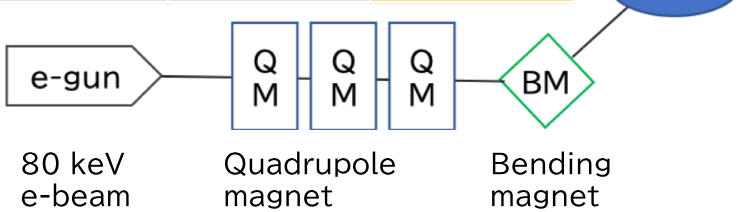


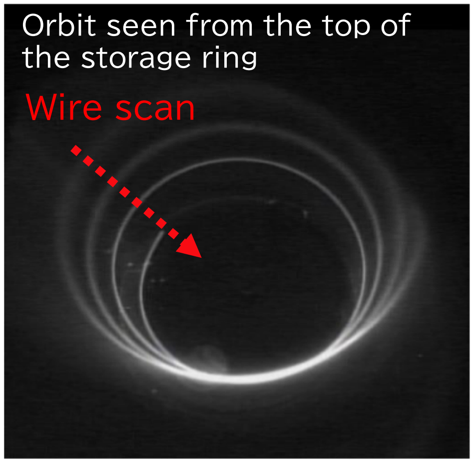
- A proof-of-principle experiment using electron beam is going well.

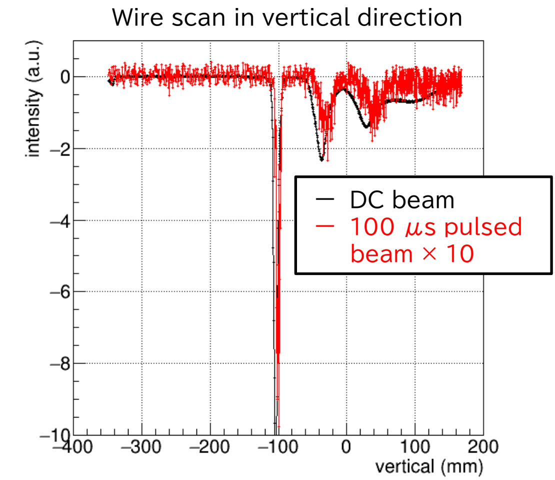
Experimental setup

	J-PARC (E34)	Electron beam test
Diameter of orbit	66 cm	24 cm
B field	3 T	82.5×10⁻⁴T
Momentum	300 MeV/c	296.9 keV/c
Cyclotron period	7.4 ns	5.0 ns
Kicker duration	130 ns	70 ns





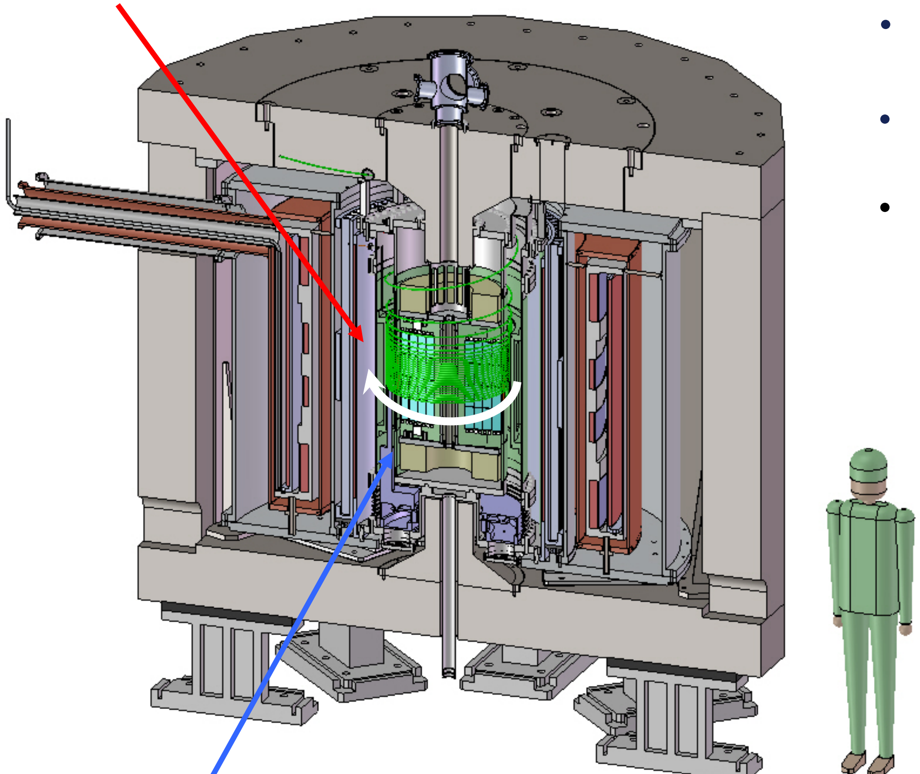




Storage magnet

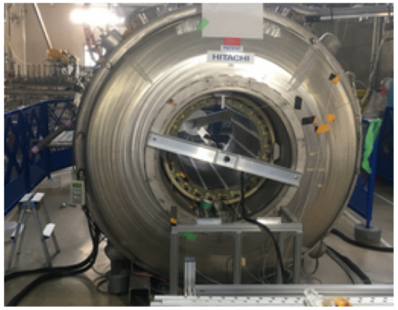
- The low-emittance muon beam frees us from magic momentum and enables us to use more precise and compact magnet.

Muon storage orbit

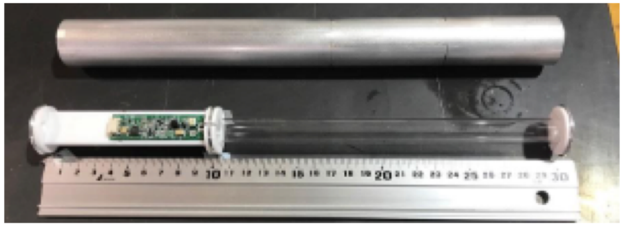


Positron tracking detector

- A 3 T MRI-type compact (ϕ 66 cm) solenoid magnet will be used to store a muon beam.
- Local uniformity of field < 1 ppm is expected.
- Shimming studies are going well using magnet for MuSEUM experiment.
- < 0.2 ppm at 1.2 T is established



- Development of NMR probe & field mapping system is also ongoing.



Positron tracking detector

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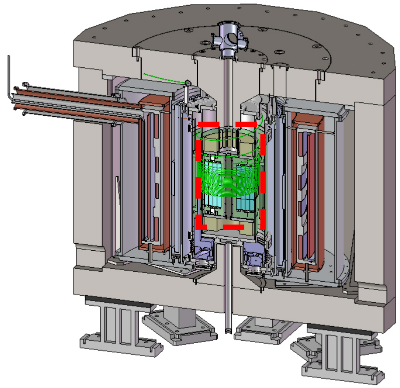
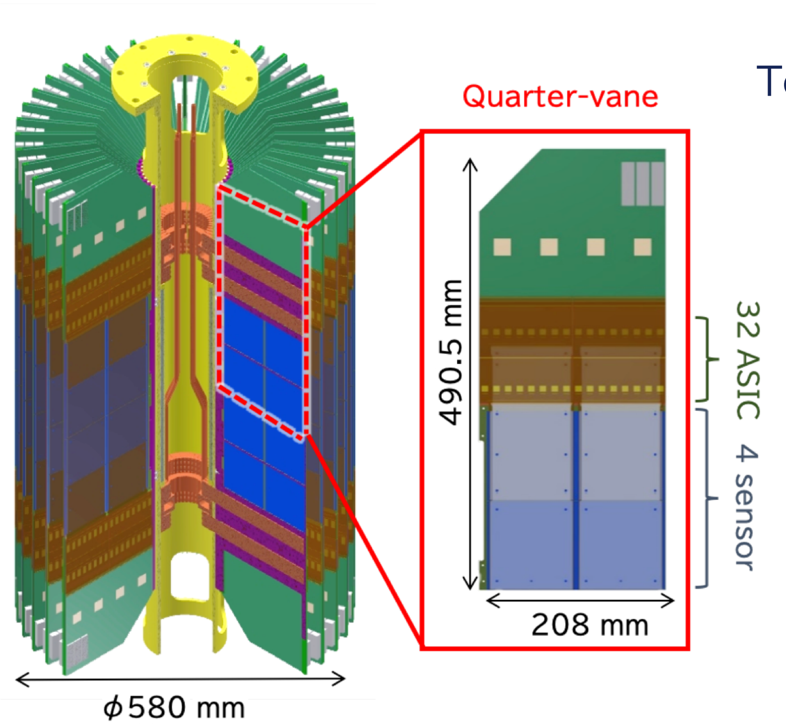
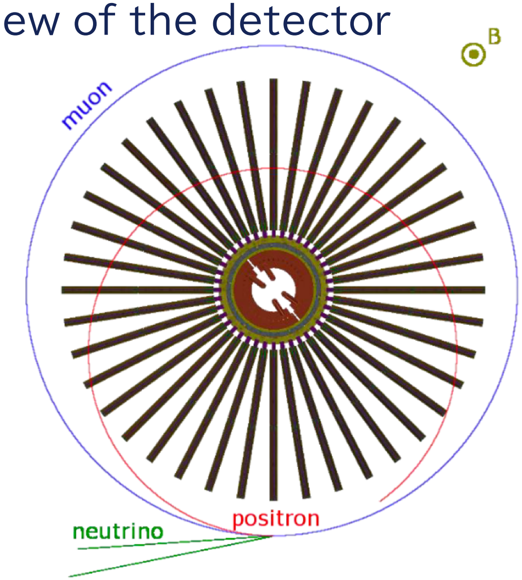
- Positrons from decay of stored muon beam are detected by the detector consisting of silicon strip sensors installed in the storage magnet.
- It consists of 40 modules called vanes (composed with 4-quarter vanes) and uses silicon strip sensors for positron detection.





Top view of the detector



Positron tracks are reconstructed by hits in radially arranged vanes.

Test assembly & cooling test is ongoing
➪ Mass production will be started from next year.

Expected sensitivities

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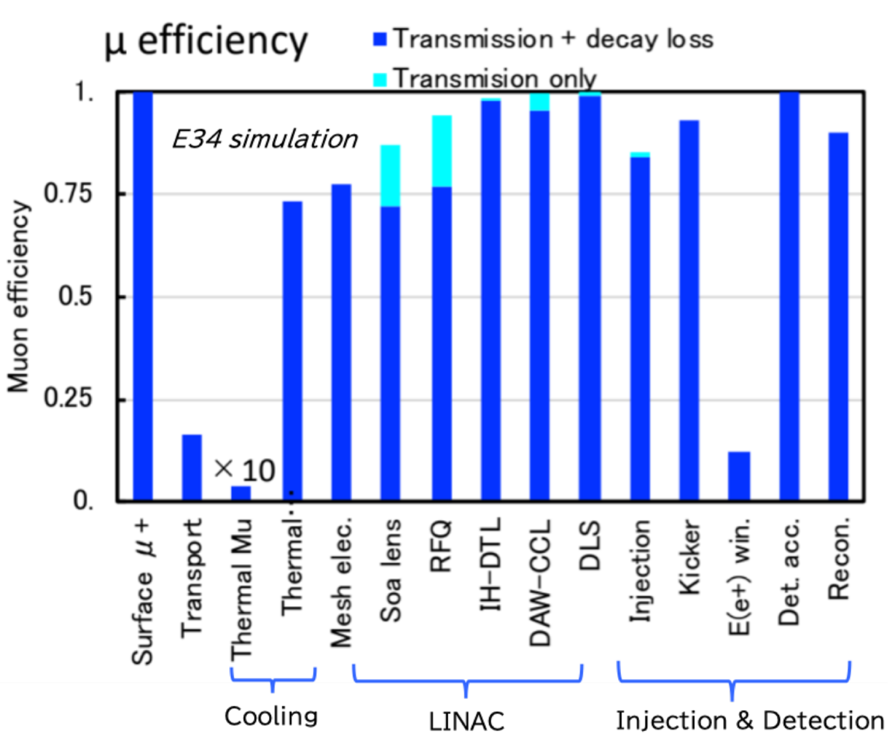

- Overall μ^+ efficiency of 1.3×10^{-5}.
- ˜2-year running will reach the BNL precision of a_μ assuming,
  - 2.2×10^7 s data taking time,
  - 1 MW proton beam,
    ➢ 5.7×10^{11} e^+'s for analysis,
  - 50% μ^+-polarization.
- Systematic uncertainties will be much smaller than statistical ones.

	Stat.	Syst.
δa_μ [ppb]	450	< 70
δEDM [10^{-21} e·cm]	1.5	0.36

Table 6. Estimated systmatic uncertainties on a_μ.

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

Schedule and milestones

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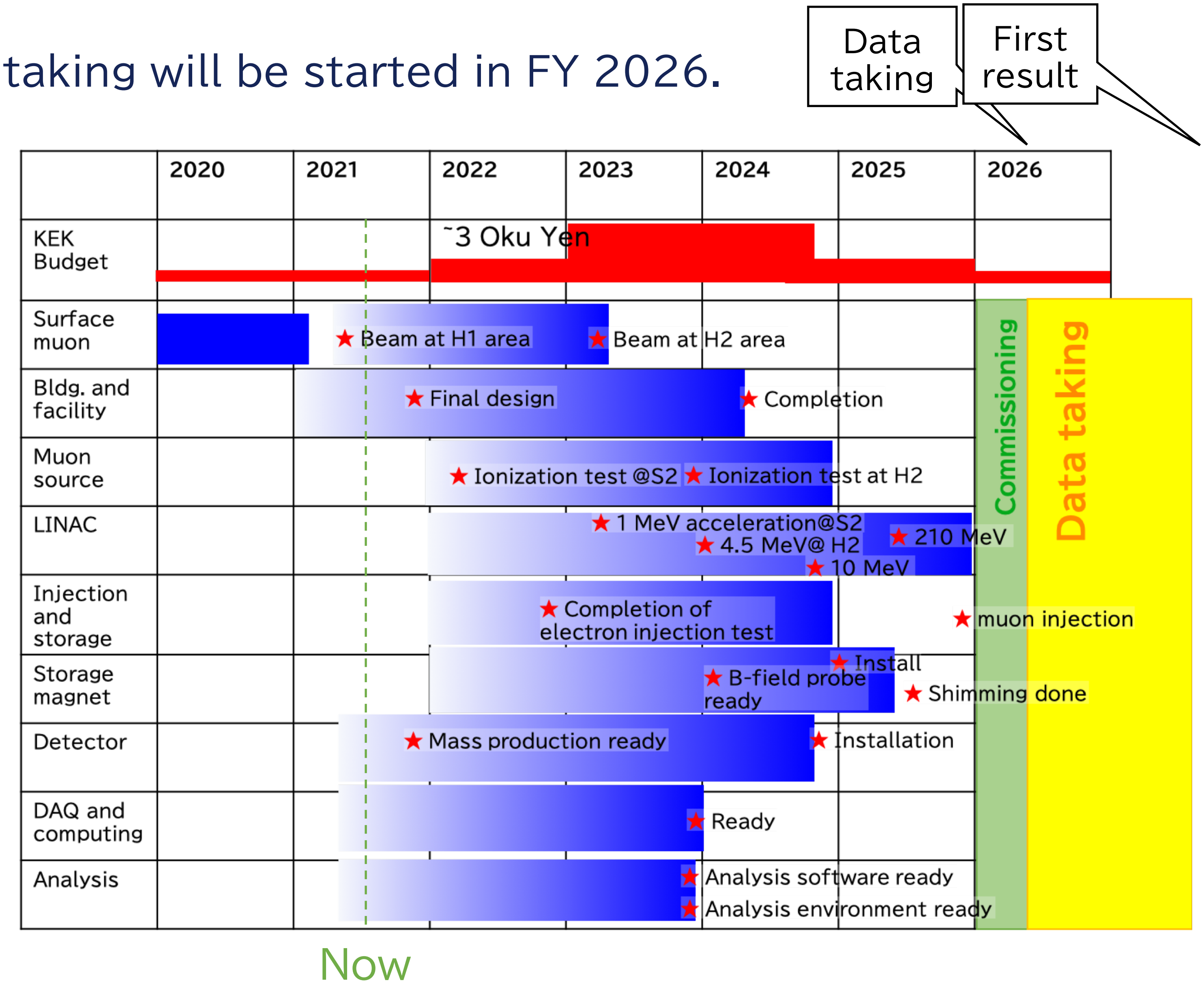
Data taking will be started in FY 2026.



Summary

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- J-PARC E34 aims to measure the muon g-2 and EDM with a new experimental approach.
  - Low emittance muon beam with no strong focusing.
  - 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 being prepared for realization.
  - The development and construction is in progress to start data taking in FY2026.
  - R&Ds of the experimental apparatus keep going well.
  - Funding requests are being made to government.
  - Intending to reach the BNL precision in ~2-year running.

References

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- E34 TDR summary
  - (https://doi.org/10.1093/ptep/ptz030)
- Muonium target
  - (https://doi.org/10.1093/ptep/ptaa145)
- Muon Linac
  - Demonstration by RFQ (https://doi.org/10.1103/PhysRevAccelBeams.21.050101)
  - IH-DTL (https://doi.org/10.1103/PhysRevAccelBeams.19.040101)
  - DAW (http://accelconf.web.cern.ch/ipac2019/papers/tuprb117.pdf)
  - DLS (https://doi.org/10.1088/1742-6596/874/1/012054)
- Injection
  - (https://doi.org/10.1016/j.nima.2016.05.126)
- Storage ring magnet
  - (https://doi.org/10.1016/j.nima.2018.01.026)
- Positron detector
  - (https://doi.org/10.1088/1748-0221/15/04/P04027)

Back up

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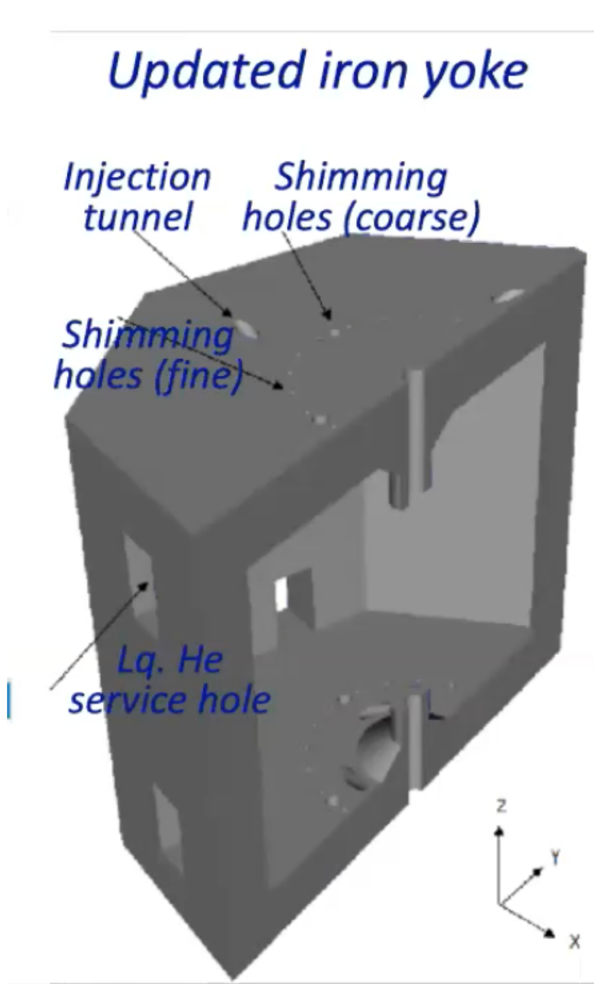
Updated iron yoke
Injection tunnel
Shimming holes (coarse)
Shimming holes (fine)
Lq. He service hole
Z
Y
X

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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		

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Table 5. Summary of statistics and uncertainties.

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

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