Muon $g-2$/EDM measurement at J-PARC

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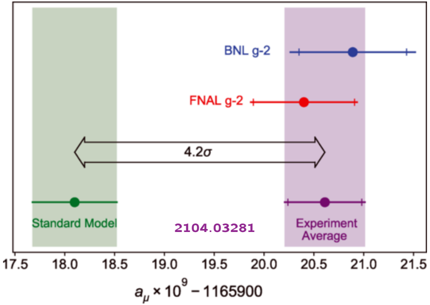
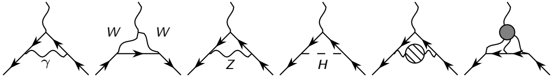
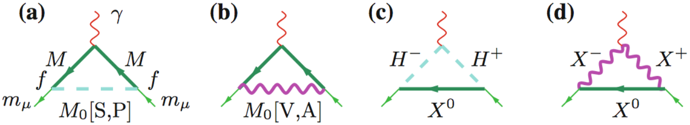
Muon $g-2$

μ is coupled to a magnetic field through a dipole moment with the Lande's g factor.
$g=2$ in the tree level or in Dirac equation.
$a=g-2$ is comes from corrections: QED, EW and QCD, and, maybe, some BSM physics.

The world average a_μ precision is 0.35 ppm.
The SM prediction is 4.2σ away from the measurement.

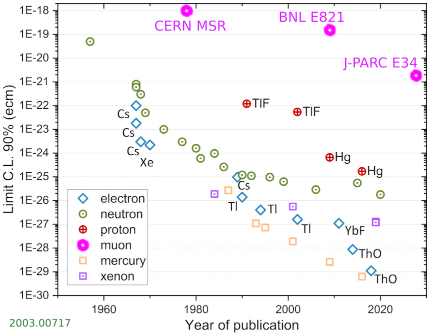






Muon EDM

The muon EDM SM expectation is $\sim 2 \times 10^{-38}\, e\,\text{cm}$.
The current experimental limit is $|d_\mu| < 1.8 \times 10^{-19}\, e\,\text{cm}$ by the BNL E821 experiment.
If non-zero EDM exists, it means T-violation.



2003.00717

Present $g_\mu - 2$ measurement technique

The spin precission frequency around momentum in *EB*-field is described by the BMT equation:

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

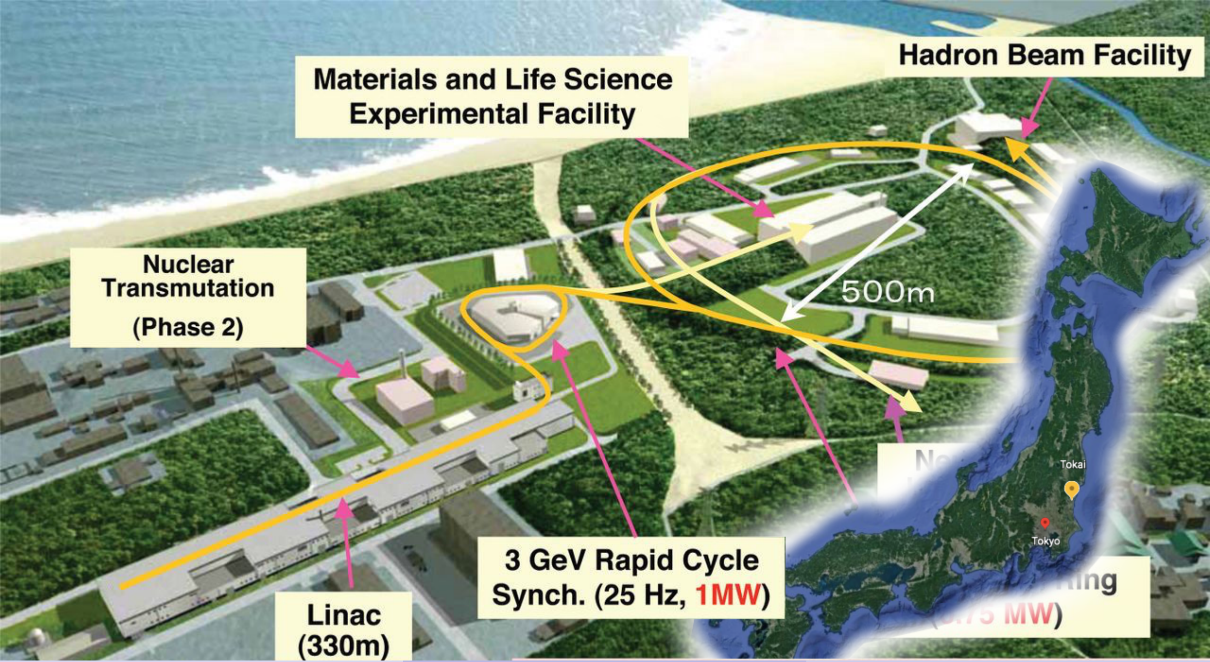
The FNAL E989 and BNL E821 employ the electric focusing in a storage ring. The *E*-field effect is cancelled because of working at "magic" momentum $p_\mu = 3094\,\mathrm{MeV}/c$.

Alternative approach

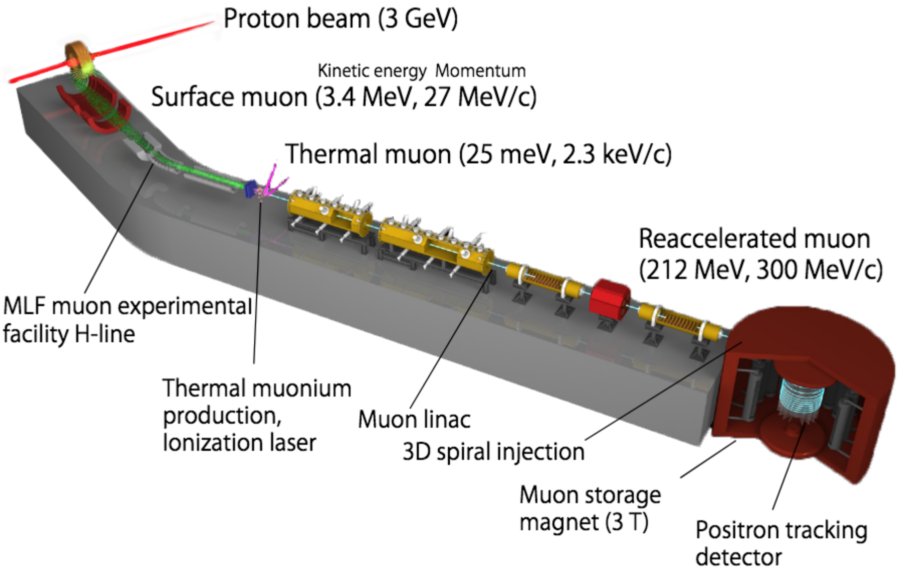
To cross-check the result it would be great to have an independent measurements based on another experimental technique.
Idea: move from the "magic" momentum to absence of E-field.

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

That would require a low emittance beam to be confided on the orbit by weak magnetic focusing.


Hadron Beam Facility
Materials and Life Science
Experimental Facility
Nuclear
Transmutation
(Phase 2)
500m
Tokai
Tokyo
3 GeV Rapid Cycle
Synch. (25 Hz, 1MW)
Linac
(330m)

E34 at J-PARC



Proton beam (3 GeV)
Kinetic energy Momentum
Surface muon (3.4 MeV, 27 MeV/c)
Thermal muon (25 meV, 2.3 keV/c)
Reaccelerated muon
(212 MeV, 300 MeV/c)
MLF muon experimental
facility H-line
Thermal muonium
production,
Ionization laser
Muon linac
3D spiral injection
Muon storage
magnet (3 T)
Positron tracking
detector

MLF and H-line

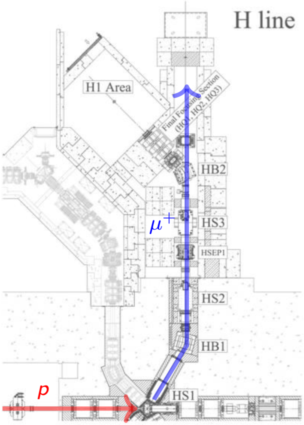
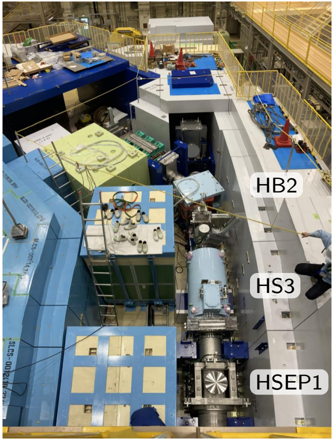


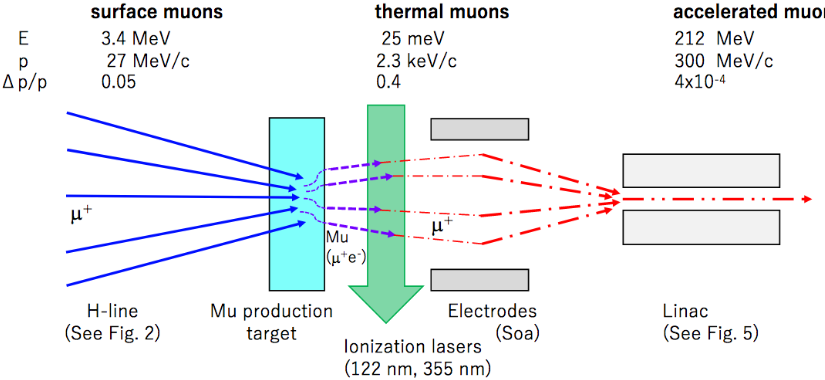
Fig. 2. The H-line layout.



- Construction of H-line has been started.
- The minimum construction of the H1-area is finished. The beginning of a beam commissioning is planed by the end of this year.
- The extension building to accommodate the H2-canal is designed. The construction area is under preparation.

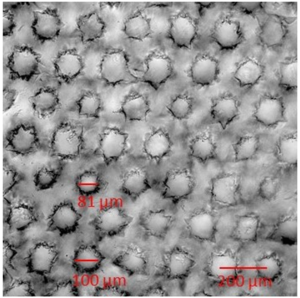
Muon thermolisation

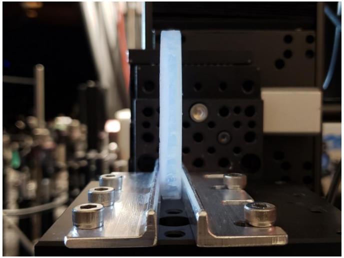
- The surface muon beam from the H-line is used as the source. Monochromatic and $\sim 100\,\%$ polarised beam.
- The muon beam is stopped at a target and muoniums ($\mu^+ e^-$ bind state) are produced.
- Diffused Mu are ionised by laser beams.

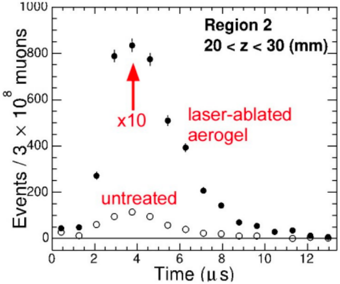


A double side laser-ablated silica aerogel target is used to thermolise μ^+ and form Mu. Various hole patterns have been studied and several day Mu emission stability was confirmed.

The current design Mu emission efficiency is ∼0.34 %, that is enough for Phase-I, but Phase-II requires improvements → multi-layer target, Mu-focusing, *etc.*

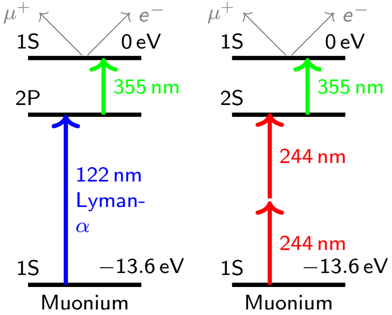


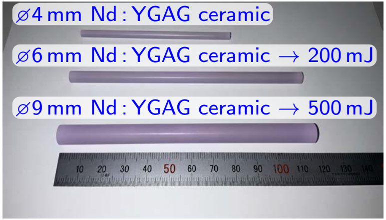




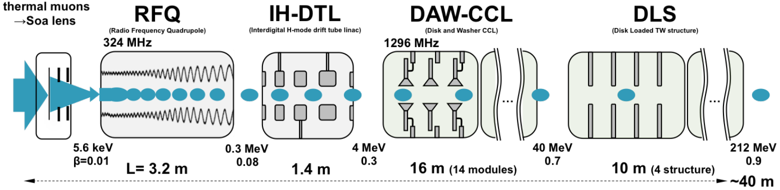
Muonium ionisation

1. Excitation, two options are considered:
    1.1 1S–2P 1-photon excitation with a Lyman-α 122 nm ~100 µJ-power laser should cover 73 % of Mu.
    1.2 1S–2S 2-photon excitation with 244 nm 200 mJ laser.
2. Dissociation 440 mJ 355 nm laser.





Muon acceleration



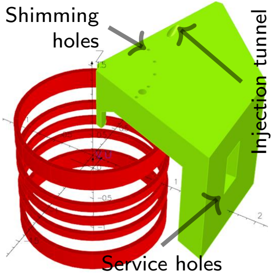
Energy	212 MeV
Intensity	$10^6\ \mu^+/\mathrm{s}$
Repetition	25 Hz
Pulse length	10 ns
Normailised ε_t	$1.5\,\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$
$\Delta p/p$	0.1 %

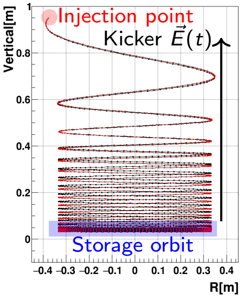
- Acceleration of Mu^- in 2018 by RFQ. Acceleration of thermal μ in 2022 in the RFQ.
- The short (1/3) prototype of IH-DTL is under a test. Full production by the end of 2021 FY.
- Production of the DAW-CCL 1st tank in 2021 FY.
- Finalising design of DLS.

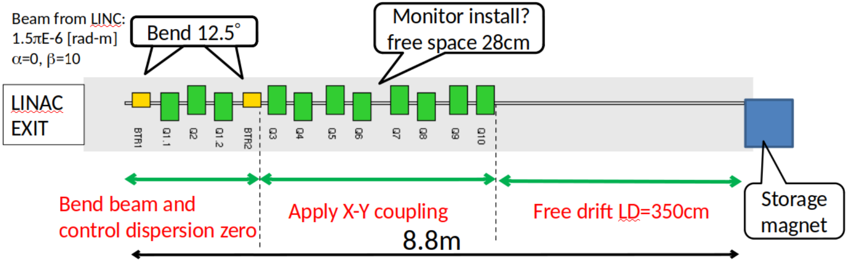
3D spiral injection

To inject the 300 MeV/c muon beam into 666 mm storage region, a 3D spiral injection scheme was developed.

Prototypes of kicker were fabricated and the injection scheme is validated using a low momentum e^- beam.

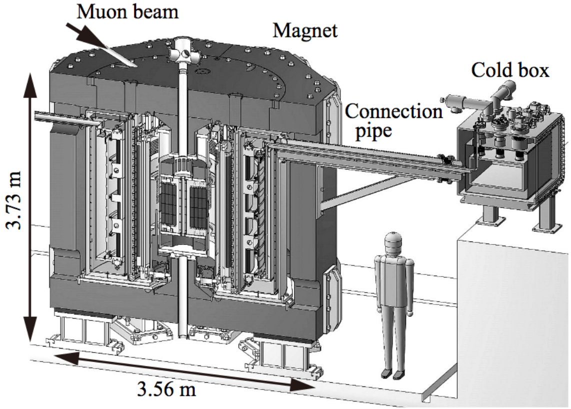


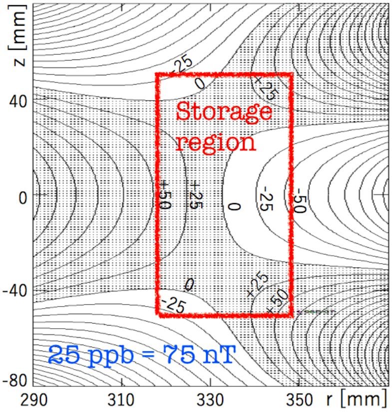




Storage magnet

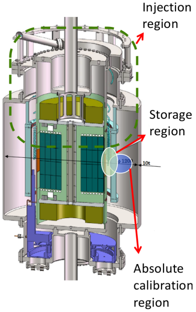
3 T MRI-type solenoid magnet will be used to store a muon beam.
Weak focusing magnetic field is also applied to keep muon beam size.

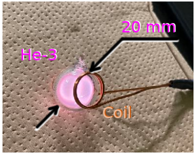


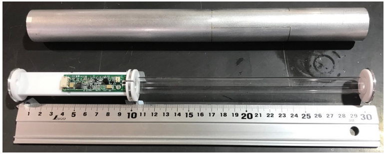


Magnetic field measurement

- High uniformity of B-field is achieved by shimming.
  - 1 ppm local uniformity was confirmed for MuSEUM.
- Hall probes: injection region, ~ 100 ppm.
- High precision water NMR probes.
  - Fixed probes: near storage region, ~ 0.05 ppm.
  - Mapping probes: storage region, ~ 0.01 ppm.
  - The standard probe was cross-calibrated between J-PARC and FNAL at Argonne NL in 2017 ($\sim 7 \pm 15$ ppb agreement).
- New NMR probes with ^{3}He are under development.
  - Smaller correction than water, but smaller signal.

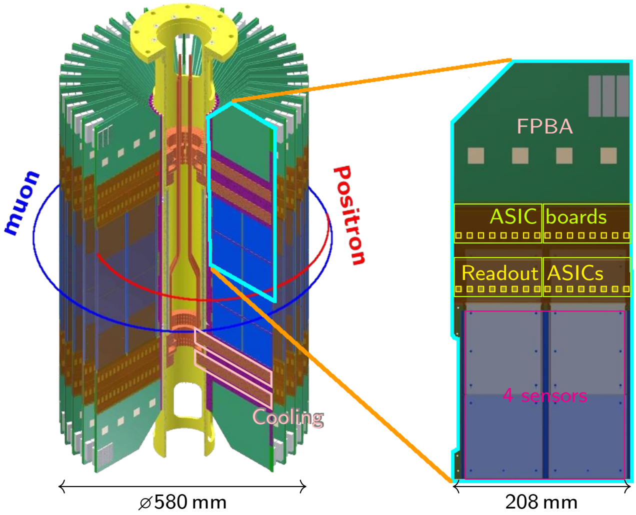




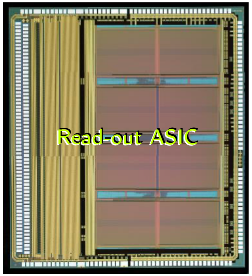


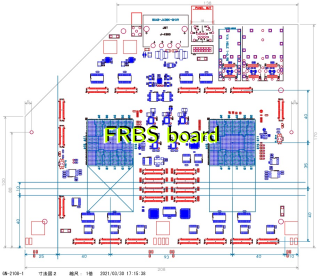
Positron tracking detector

- Positrons from decay of stored muon beam are detected by silicon strip sensors installed in the storage magnet.
  - Positron tracks are reconstructed from hits in radially arranged 40 modules.
- Each vane has silicon strip sensors in both sides with their strip directions orthogonal each other.



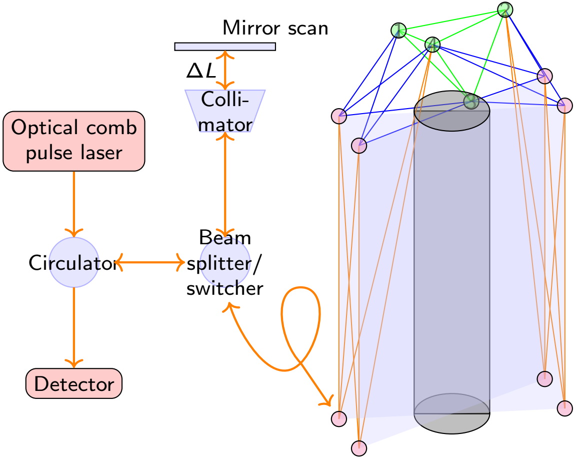
Detector components





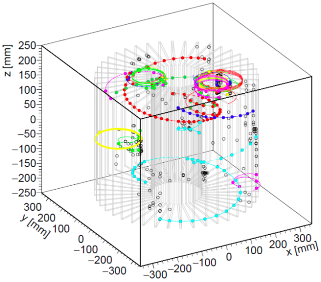
Detector alignment system

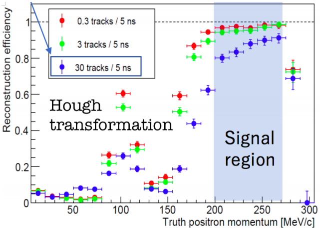
- To achieve 10^{-21} $e\,$cm sensitivity of the EDM, position of sensors on the detector need to be controlled with precision better than 1 μm.
- Detector assembly with 1 μm accuracy in the sensor plane is under development (3 μm was achieved so far).
- Alignment/deformation monitor based on 3D-length measurement grid of absolute distance interferometers.
- A way to measure sensor positions using e^+ tracks is also being developed.

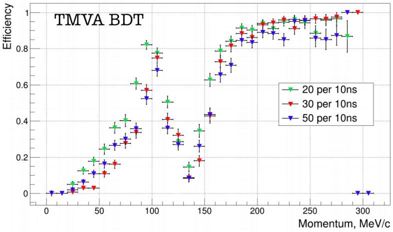


Track reconstruction

- SW based on Geant4 and ROOT provides the full chain from primary generation of injected μ^+ to reconstructed e^+ tracks.
- Track finding in the high density real track condition is challenging.
- 2 track finding algorithms are developed:
  - Using Hough transform
  - TMVA BDT
- End-to-end simulation, from the μ target to the storage magnet: the plan is to increase statistic and then study systematics.

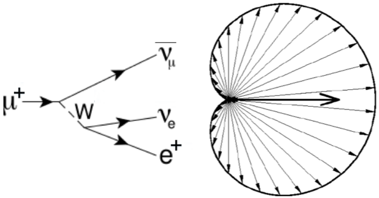


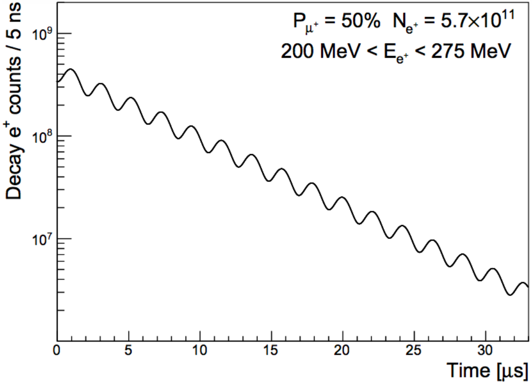




$g_\mu - 2$ measurement

The time dependency of the number of e^+ with a cut on p reveals an oscillation pattern directly linked to ω.
Alternatively, it is possible to use ratio of data taken with opposite initial spin.

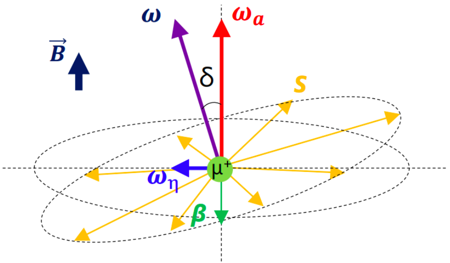


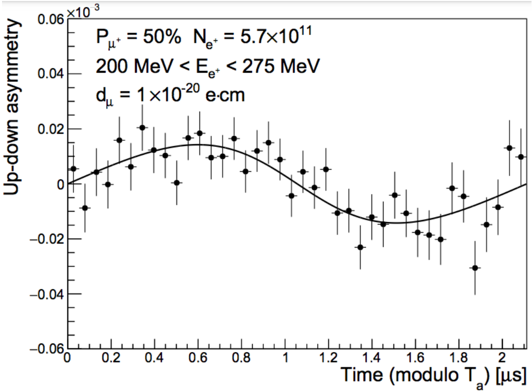


EDM measurement

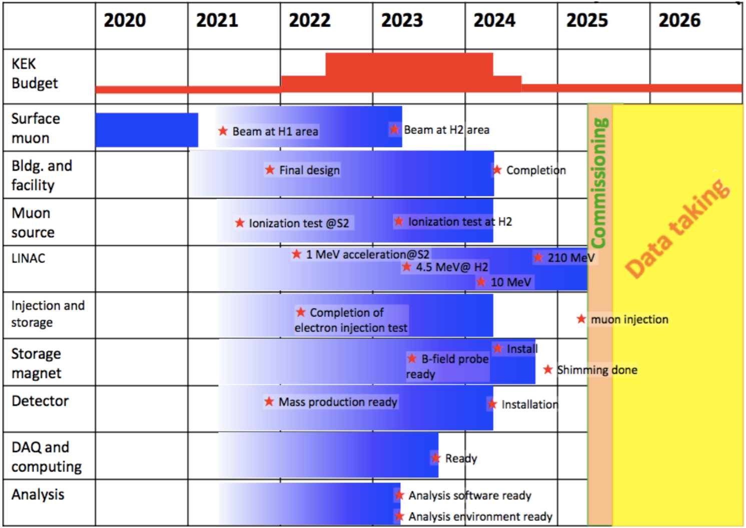
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = -a\frac{q}{m}\vec{B} - \eta\frac{q}{2m}\vec{\beta}\times\vec{B}.$$

The tilt of the angular velocity vector is observed as an asymmetry between up-going and down-going decay e^+s.





Schedule



- KEK-SAC endorsed the experiment for the near-term priority in 2019.
- KEK requests construction funding from the Japanese government (MEXT) in 2021.
- The key components are under development by the JSPS grant-in-aid from 2020.

Comparison

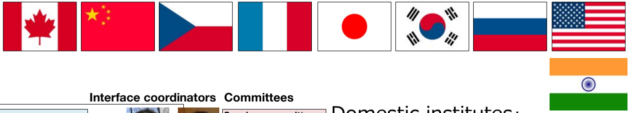
	BNL	FNAL		J-PARC
		Run 1	Final	
Muon momentum	3.09 GeV/c			300 MeV/c
Lorentz γ	29.3			3
Polarisation	100 %			50 %
Storage field	$B = 1.45\,\mathrm{T} + E$			$B = 3.0\,\mathrm{T}$
Focusing field	Electric quadrupole			Very weak magnetic
Cyclotron period	149 ns			7.4 ns
Number of detected e^+	5.0×10^9		1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9		–	–
a_μ precision (stat.)	460 ppb	434 ppb	100 ppb	450 ppb
(syst.)	280 ppb	$157 \oplus 25$ ppb	100 ppb	< 70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19}\ e\,\mathrm{cm}$	–	–	$1.5 \times 10^{-21}\ e\,\mathrm{cm}$
(syst.)	$0.9 \times 10^{-19}\ e\,\mathrm{cm}$	–	–	$0.36 \times 10^{-21}\ e\,\mathrm{cm}$

Collaboration

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

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



Subgroups

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

Interface coordinators

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

Committees

Speakers committee
chair: K.Ishida, E. Won

Publication committee
chair: S. Eidelman

Domestic institutes:
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.

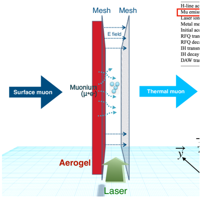
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

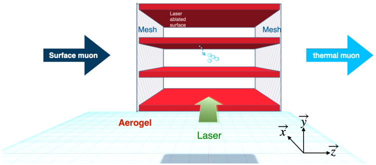
Summary

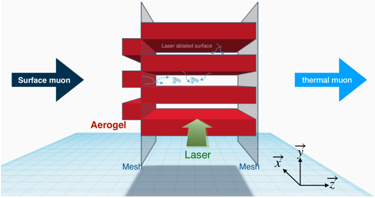
- In the J-PARC E34 experiment, measurement of muon $g-2$ and EDM is planned with a method different from BNL/FNAL.
    - Re-accelerated thermal μ^+.
    - Beam storage with no electric field.
    - The 300 MeV/c momentum μ^+ beam opens an opportunity for the compact storage region with highly uniform magnetic field.
    - The decay e^+ tracking detector can work in pile-up environment and measure $\vec{p}_{e^+}$, which is required for the $g-2$/EDM determination.
- Construction of the beam line has been started and other components of the experiment are also moved to the construction phase.
- The experiment aims to start data taking from 2025.

Fin

Aerogel target modification







- The validation Mu emission from multi-target aerogel experiment is proposed.
- Mu emission under various conditions are simulated and compared. With reflection, about 1.6 times higher yield is estimated in two-piece targets than in the current design.
- Design of the new target holder is ongoing, as well as detailed evaluation of the accelerated μ^+ beam at RFQ.
- See talk by C. Zhang at E34 CM22 https://kds.kek.jp/event/38051.

From ω_a to a_μ

- Magnetic field measurement

$$B = \frac{\hbar\omega_p}{2\mu_p}$$

ω_p — proton Larmor frequency in water.

- $\omega_a = \frac{e}{m_\mu c} aB$
- $\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu c}$

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

$g-2$ — Fermilab E989, J-PARC E34

$$a_\mu = \frac{\omega_a/\omega_p}{\omega_a/\omega_p - \mu_\mu/\mu_p}$$

$$a_\mu = \frac{\omega_a}{\omega_p} \cdot \underbrace{\frac{\mu_p}{\mu_e}}_{\text{8 ppb}} \cdot \underbrace{\frac{\mu_\mu}{\mu_e}}_{\text{120 ppb}} \cdot \underbrace{\frac{g_e}{2}}_{\text{0.3 ppt}}$$

MuSEUM (J-PARC) — **Mu HFS**

Mu 1S-2S — Mu-MASS (PSI), new exp. (J-PARC)

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_{\text{inf}} \frac{\mu_\mu}{\mu_B}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

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