Muon g-2/EDM experiment at J-PARC

Katsu Ishida (RIKEN)
on behalf of the J-PARC muon g-2/EDM collaboration (E34)

Outline
- concept overview
- progress, update
- schedule, collaboration
- summary
Muon g-2/EDM experiment at J-PARC

Aims for measurement of muon g-2 independent of BNL and FNL experiments

Phase 1 : 0.45 ppm
Phase 2 : 0.1 ppm

by quite different method
using several novel techniques

very low emittance muon beam
muon LINAC acceleration from thermal energy
MRI-type high-precision muon storage magnet
Full tracking detector
muon g-2 and EDM measurements

In uniform magnetic field, muon spin rotates ahead of momentum due to $g\cdot 2 = 0$

general form of spin precession vector:

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

BNL E821 approach
\(\gamma = 30\) (\(P = 3\) GeV/c)

FNAL E989

J-PARC approach
\(E = 0\) at any \(\gamma\)

J-PARC E34
Fermi Muon g-2/EDM Experiment

- Based on 3 GeV magic momentum muon beam
  - Muon from high-energy pion decay line at Fermi-lab
  - High precision muon storage ring with 14 m diameter
  - Muon injection kicker
  - Strong focusing with quadrupole electrode
  - Positron detection with calorimeters and tracking detectors
Basis of our method

- Very low emittance (cooling) muon beam by reacceleration of thermal energy muon
  - No need of strong focusing E-field
    - no restriction on muon momentum
  - MRI type compact precision magnet
  - Full tracking detector
- Thermal energy muon source made by
  \[ \pi^+ + \mu^+ \rightarrow \mu^+ \text{ cooling emittance } \sim 1000\pi \text{ mm } \cdot \text{mrad} \]
  \[ \mu^+ \text{ emittance } 1\pi \text{ mm } \cdot \text{mrad} \]
Muon g-2/EDM Experiment at J-PARC: overview

Goals:
- g-2: 450 ppb (~BNL/FNAL run 1)
- EDM: $1.5 \times 10^{-21}$ e cm (x70 better)
Primary muon beam production: J-PARC MLF

- J-PARC MLF (Materials and Life Science Facility)
  - 1 MW 3 GeV proton beam for neutron and muon production

Muon Facility (MUSE)
Four muon beam lines (D-, U-, S- and H-line)
Muon g-2/EDM at H-line
Muon Beam Line and Experimental Area

New muon beamline "H-line" is under construction

• Beam was delivered to H1 area in early 2022:
  for μe-conversion (DeeMe) and Mu-HFS (MuSEUM)
• Beam planned to H2 area (for muon g-2) in 2023
  beamline components, radiation shielding, ...

New extension building ready for construction

Confirmation of muon intensity (~10⁸/s)
by muon decay events in H1

(Preliminary)
Concept of low emittance muon beam production by reacceleration of thermal muon

<table>
<thead>
<tr>
<th></th>
<th>surface muon</th>
<th>thermal muon</th>
<th>accelerated muon</th>
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</thead>
<tbody>
<tr>
<td>E (MeV)</td>
<td>3.4</td>
<td>30</td>
<td>212</td>
</tr>
<tr>
<td>p (MeV/c)</td>
<td>27</td>
<td>2.3</td>
<td>300</td>
</tr>
<tr>
<td>$\Delta p/p$</td>
<td>0.05</td>
<td>0.4</td>
<td>4x10^{-4}</td>
</tr>
</tbody>
</table>

 Ionization Laser (122 nm, 355 nm)

$\Delta p_T/p \sim 3 \text{ keV} / 300 \text{ MeV} = 1 \times 10^{-5}$
Making thermal energy muon

- Silica Aerogel as Muonium (=μ⁺e⁻) source
  - Surface muons (~4 MeV) are converted to thermal muonium
  - Cooling from 4 MeV to 0.03 eV (x10⁻⁸)
  - Laser ablation of silica aerogel increased thermal Mu efficiency

P. Bakule et al., PTEP 2013, 103C01
G. Beer et al., PTEP 2014, 091C01
G. Beare et al., PTEP 2020, 123C01

Larger size and less deforming ablated aerogel (at UBC)

- Hole opening fraction
- Yield dependence on target condition
Making muon source with laser Ionization

- Mu ionization with laser (for \( \mu^+ \) acceleration)

  Two schemes are considered for Mu ionization
  
  Mu 1S-2P excitation at U-line
  
  - Efficient single photon excitation
  - Challenging 100 \( \mu \)J Lyman-\( \alpha \) laser development

  Mu 1S-2S excitation at S-line
  
  - Established 244 nm laser technology
  - Demonstration started in S2-line

Ionization of Mu form silica aerogel was confirmed this year by both methods

Now comparing the measured efficiency with simulation

Intense Lyman-\( \alpha \) 4 \( \mu \)J at U-line (goal 100 \( \mu \)J with longer wave mixing chamber in H-line)

Mu Ionization in S2-line for 1S-2S spectroscopy
High power 244 nm laser development in progress
Muon acceleration: initial stage

- From thermal energy to MeV
  - First step: degraded sub-keV Mu- to RFQ (89 keV)
    - demonstration in 2017
    - bunch structure measurement 2018
  - Second step: thermal energy muon (~0.03 eV) to RFQ
    - high efficiency and high-quality beam
    - demonstration planned in S2-line in early 2023

World first muon RF acceleration
Bunch width monitor
Further acceleration of muons with LINAC

- The rest of muon LINAC cavities are designed and evaluated for acceleration to 212 MeV (300 MeV/c)
  Staging design for fast muon acceleration covering wide β region

Test with thermal muon in 2023
Proto-cavity power test, Real cavity production
First real tank is fabricated
Prototype fabrication in 2022FY

Thanks to Special Promotion Grant-in-aid 2020-2025 (Kakenhi)
Spiral Muon Injection

• For injection of muon beam into compact storage ring, 3D spiral injection scheme has been invented
  • Smooth connection between injection and storage regions
  • Pulsed magnetic kicker to guide muons to stable orbit
  • Weak-focusing magnetic field to control muons in a few cm
  
  Injection efficiency: ~85%


Test experiment using electron beam is progressing
  • 297 keV/c e- and 8.25 mT, 24cmφ (versus 300 MeV/c and 3 T, 66cmφ)
  • Visualization of 3-D spiral geometry with CCD camera
  • Test of beam shape effect and proto-type kicker

Injection, kicker and storage simulation
Muon Storage Magnet and Field Measurement

- 3T MRI-type superconducting solenoid magnet

Demonstration of sub-ppm field shimming at 1.2 T using MuSEUM magnet

Cross-calibration of FNAL and J-PARC field probes at ANL at 1.45 and 1.7 T in 2019 (3 T study planned)
Detector and Analysis

- Positrons tracks are reconstructed by **Silicon-strip detector**
  - Mass production in progress
  - Readout ASIC was developed for this detector (*IEEE TNS 67, 2089(2020)*)
  - Prototype modules were tested at J-PARC and ELPH (*JINST 15 P04027 (2020)*)

![Detector Diagram](image)
Detector and Analysis

- Simulation and track reconstruction software package being developed

Reconstruction of positron energy and timing gives g-2 precession pattern
End to end simulation

- Software package is being developed to make end-to-end simulation
  - $1.8 \times 10^6$ muons simulated at LINAC exit in 2020
  - 10 times more in 2022 will be used for statistics and systematics study
  - $\sim 10^9$ will be needed for systematics in timing shift by pile-up, sensor alignment using tracks
Statistical and systematic uncertainties

Summary of statistical uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimation (ppb)</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of muons in the storage magnet</td>
<td>$5.2 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>Total number of reconstructed $e^+$ in the energy window [200, 275 MeV]</td>
<td>$5.7 \times 10^{11}$</td>
<td></td>
</tr>
<tr>
<td>Effective analyzing power</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty on $\omega_\mu$ [ppb]</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Uncertainties on $a_\mu$ [ppb]</td>
<td>450 (stat.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 70 (syst.)</td>
<td></td>
</tr>
<tr>
<td>Uncertainties on EDM $[10^{-21} \text{ e}\cdot\text{cm}]$</td>
<td>1.5 (stat.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36 (syst.)</td>
<td></td>
</tr>
</tbody>
</table>

Estimated systematic uncertainties on $a_\mu$

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimation (ppb)</th>
<th>Source</th>
<th>Estimation (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomalous spin precession ($\omega_\mu$)</td>
<td></td>
<td>Magnetic field ($\omega_\mu$)</td>
<td></td>
</tr>
<tr>
<td>Timing shift</td>
<td>&lt; 36</td>
<td>Absolute calibration</td>
<td>25</td>
</tr>
<tr>
<td>Pitch effect</td>
<td>13</td>
<td>Calibration of mapping probe</td>
<td>20</td>
</tr>
<tr>
<td>Electric field</td>
<td>10</td>
<td>Position of mapping probe</td>
<td>45</td>
</tr>
<tr>
<td>Delayed positrons</td>
<td>0.8</td>
<td>Field decay</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Differential decay</td>
<td>1.5</td>
<td>Eddy current from kicker</td>
<td>0.1</td>
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<tr>
<td>Quadratic sum</td>
<td>&lt; 40</td>
<td>Quadratic sum</td>
<td>56</td>
</tr>
</tbody>
</table>
EDM Measurement

EDM measurement relies on the tilt of muon precession to the mid plane

- No E-field simplifies the measurement

\[ \vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = -a \frac{q}{m} \vec{B} - \eta \frac{q}{2m} (\vec{\beta} \times \vec{B}) \]

- To be observed in up-down asymmetry
- \( \tan \delta = \omega_\eta / \omega_a = \eta \beta / 2a \)
- Good detector alignment precision is essential
- to aim at \( 10^{-21} \) e cm sensitivity (\( 10^{-5} \) rad)
- 1 \( \mu \)m detector alignment is developed

(E34 simulation)
### Comparison of Parameters

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

*phase 1 ~250 days*
Collaboration Status

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

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

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. Linuma
- Storage magnet, field measurements
- Detector
  leader: T. Yoshioka
- DAQ and computing
  leader: Y. Sato, (K. Hayasaka)
- Analysis
  leader: T. Yamanaka

Interface coordinators
- K. Ishida
- M. Otani
- Y. Kondo
- H. Linuma
- T. Kume
- Y. Sato
- T. Suehara
- T. Yamanaka

Committees
- Speakers committee
  chair: K. Ishida
- Publication committee
  chair: B. Shwartz

New
Welcome University of Groningen

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

The 24th J-PARC muon g-2/EDM collaboration meeting, June 8-10, 2022
## Schedule

<table>
<thead>
<tr>
<th></th>
<th>2021 (FY)</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027 and beyond</th>
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<td>KEK Budget</td>
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<td>Surface muon</td>
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<td>Bldg. and facility</td>
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<td>Muon source</td>
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<td>LINAC</td>
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<td>Injection and storage</td>
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<td>Storage magnet</td>
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<td>Detector</td>
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<td>DAQ and computing</td>
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<tr>
<td>Analysis</td>
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</tr>
</tbody>
</table>

- **Beam at H1 area**
- **Beam at H2 area**
- **Final design**
- **Completion**
- **Ionization test @S2**
- **Ionization test at H2**
- **80keV acceleration@S2**
- **4.3 MeV@ H2**
- **Fabrication complete**
- **210 MeV**
- **B-field probe ready**
- **Install**
- **Install**
- **Shimming done**
- **Quoter vane prototype**
- **Mass production ready**
- **grid service open**
- **small DAQ system**
- **common computing operation test resource usage start**
- **Ready**
- **Tracking software ready**
- **Analysis software ready**

★ **Milestones – many in this FY**

---

Here

2 years for the first result
Summary

• **muon g-2/EDM experiment at JPARC** aims to measure muon g-2 and EDM with a new experimental approach
  - Low emittance muon beam
  - MRI-type storage ring with good injection efficiency and highly uniform B-field
  - Full tracking detector with large acceptance

• The experiment is getting ready for realization
  - Construction of new muon beam line (H-line) and building design
  - Achieving many R&D and test milestones
  - Production of the subsystems are ongoing

• Expecting data taking to start in FY2027
  + 2 years run for 1st result
Thank you for your attention.