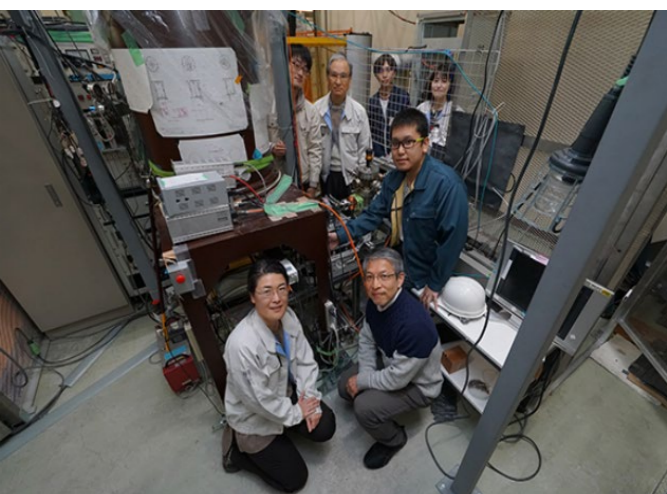


Challenging quest of three-dimensional spiral injection scheme to store the 80 keV electron beam in 12 cm diameter ring for New Muon g-2/EDM experiment at J-PARC (E34)



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1. Physics goal: Explore the beyond standard model

g-2
 $a_\mu = \frac{g-2}{2} = \dots$
 g-2: 0.35ppm (exp.)
 4.2σ discrepancy from the standard model
 (*) combined two experiments: E895@FNAL, Phys. Rev. Lett. 126, 141801(2021) & E821@BNL, Phys. Rev. D 73, 072003, 2006
 *1: arXiv:2308.06230v1 [hep-ex] 11 Aug 2023

EDM
 Standard Model expects $\sim 2 \times 10^{-38}$ e·cm
 Upper limit (E821) $< 1.9 \times 10^{-19}$ e·cm (90% CL)
 E821@BNL, Phys. Rev. D 80, 052008, 2009

Goal:
 g-2: 0.45ppm (statistical uncertainty)
 (2023-E989 0.20ppm (*1))
 EDM sensitivity: 1.5×10^{-21} e·cm

Non-zero observation = new physics
 14m
 J-PARC E34 ring size image

2. Muon spin precession probes g-2 and EDM...catch the new physics!

We measure $\vec{\omega}_a = \text{Spin motion} - \text{cyclotron motion}$

$$\vec{\omega}_a = \frac{q}{m} \left[\left(\frac{g-2}{2} \right) \vec{B} - \left(\frac{g-2}{2} - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right] + \frac{\epsilon_{EDM}}{2} (\vec{\beta} \times \vec{B}) + \frac{\epsilon_{EDM}}{2} \frac{\vec{E}}{E^2}$$

Assuming EDM upper limit $\sim 1e-19$ e·cm

$\vec{\omega}_{SPIN} = \frac{e}{m_\mu} \frac{g-2}{2} \vec{B} + \frac{2c}{h} \eta_{EDM} (\vec{\beta} \times \vec{B})$

- Electric field $\vec{E}=0$
- Store muon beam in the uniform magnetic field (<0.1 ppm)
- Very precise control of the muon storage orbit
- Angle between $\vec{\omega}_a$ and magnetic field \vec{B} is estimated to be 1mrad assuming EDM upper limit from the previous experiment.
- If we measure such angle with 0.01mrad precision, we perform very precise EDM measurement with 100 better sensitivity than previous exp.

Super precise adjustment for muon storage magnetic field is a KEY

3. Compact storage ring applying medical MRI type superconducting magnet technology, requires newly developing 3-D spiral injection scheme!

Expect to perform ± 0.1 ppm of high uniformity of three Tesla magnetic field

Magnetic field of 3T, 300MeV/c muon beam
 → Diameter of storage orbit is only 0.66m.

3-D spiral injection (side view)
 Beam injection
 Superconducting coils (Five thick coils)
 Fringe field
 Fiducial volume
 Vertical kick
 Main solenoid coil

Utilize fringe field
 Radial field B_R deflects beam direction and changes θ
 2-D orbit
 After the kick
 10mm-0.4mrad
 Target: $n=1.5E-4$

Effective radial kicker field
 $= B_{R0}(r, z) + B_R(z) \sin \frac{2\pi}{T_{kick}} (t - t_0)$

Half-sin shape current for vertical kick
 $I(t) = I_0 \sin \left(\frac{\pi}{T_{kick}} (t - t_0) \right); (t - t_0) < T_{kick}$
 $= 0; (t - t_0) > T_{kick}$

Weak Focus both direction
 $<n < 1$: focus radially and vertically

Mission of the beam transport line:

- Transport muon beam from the exit of the muon LINAC to the injection point of the storage magnet
- Apply appropriate "X-Y coupling" for "3-D spiral beam injection"
- Control injection angle (beam line slope of 26 degree)

Beauties:
 Smooth connection between injection and storage sections without any sources of error field
 A unit of magnet does work for this method and decrease sources of error field

4. Beam monitor inside the storage magnet: How do we control the beam?

Reconstruct z-z' time snap by use of (4) & (5)

600ns after injection

W/o Sci-Fi w/ Sci-Fi

Good injection MC truth Reconstructed

Active Shield Steering Magnet: Control beam position/pitch angle at $z \sim 0.95$ m

Beam position/profile monitor

Pulse Kicker

Pillar scintillator detector: detect time stamp of muon decay

Silicon detector (Partial)

5. Development for 3-D spiral injection scheme by use of 80 keV electron gun

preparation-1: X-Y coupled beam by rotating Quads.

80keV Electron-gun
 Storage magnet (solenoid 80Gauss)
 Rotating Quads for X-Y coupling
 Q1 Q2 Q3

X-Y coupling control by use of three rotating quadrupoles is the key for 3-D spiral injection

Q-scan by use of single quadrupole (Q1 or Q2 or Q3)
 Change K-value of Q1 (or Q2 or Q3) to measure focus and defocus beam shape
 Reconstruct σ_0 (at initial point)
 Estimate σ_1 at the end of the transport line

Q-scan can measure $\sigma_0 = M \sigma_0(M)^t$

Q-scan by use of three quads.
 Vertical scan
 Horizontal scan

At least four independent set-up data can solve 10 unknown parameters, in principle.
 Q-scan data is a kind of special data set

20 different Q settings for σ_0 measurement
 Every set-up has different $m_{11} \sim m_{44}$ and three measurements: $\langle x^2 \rangle, \langle y^2 \rangle$ and $\langle xy \rangle$

3 data for each set-up

$X = T X_0$
 $X_0 = [T^t T]^{-1} T^t X$

We can get initial beam σ -matrix from beam x-y shape at copper position, in principle

preparation-2: kicker and "simple SiFi monitor" install

Kicker coil
 injection 2022/Mar.

SiFi = Scintillating fiber

Detect stored beam
 Main probe
 17 cm
 30 mm

Upper and lower coils with opposite pulse current create pulse radial field

120nsec Kicker current by Rogowski coil

Funny time dependent signals are detected...what happened!
 120nsec kicker
 0 degree 45 degree 90 degree 135 degree 180 degree

Very preliminary
 Stored beam detected by scintillating fiber monitor. Injected beam of 100ns width, and stored beam signal continues more than 500ns!
 Reflected beam by kicker/fringe field hits lower loss monitor set in the bottom

preparation-3: "lyre shaped SiFi monitor" install

3-D spiral beam and new monitor image
 150mm
 55mm

Expected eccentric trajectory for a single particle (simulation)

Expected signals from new monitor
 170ns, 220ns, 270ns, 320ns, 370ns, 420ns, 470ns

Summary and Future
 Preparation for a new precise experiment for muon g-2 and EDM (E34) is ongoing. We expect the first beam in FY2028.
 3-dimensional spiral injection is a key for new experiment, and feasibility studies shown here.
 X-Y coupled beam is controlled by rotating quadrupole magnets. Q-scan and sigma-matrix measurements are introduced.
 Stored beam guided by kicker is detected. New lyre shape SiFi monitor will strong tool to understand "eccentric trajectory".
 Feasibility study goes well and many knowledge will be reflected on the new J-PARC E34.

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<https://g-2.kek.jp/>

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References
 [1] M. Abe and J-PARC g-2/EDM Collaboration, Prog. Theor. Exp. Phys. 2019, 053C02, 2019.
 [2] M. Abe, Y. Murata, H. Iinuma, T. Ogitsu, N. Saito, K. Sasaki, T. Mibe, H. Nakayama, Nuclear Inst. and Methods in Physics Research, A. Vol. 890, 2018, PP. 51–63.
 [3] H. Iinuma, H. Nakayama, K. Oide, K. Sasaki, N. Saito, T. Mibe, and M. Abe, Nuclear Instruments and Methods in Physics Research A, 832, 2016, pp51–62.
 [4] H. Iinuma, M. Abe, K. Sasaki, H. Nakayama, T. Mibe, T. Takayanagi and A. Tokuchi, TUP036, Proceedings of the 19th Annual Meeting of Particle Accelerator Society of Japan, PASJ2022. https://www.pasj.jp/web_publish/pasj2022/proceedings/PDF/TUP036.pdf
 [5] H. Iinuma, H. Nakayama, M. Abe, K. Sasaki and T. Mibe, IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1–5, Sept. 2022, Art no. 4004705, doi: 10.1109/TASC.2022.3161889
 [6] H. Iinuma, "Precise control of a strong X-Y coupling beam transportation for J-PARC muon g-2/EDM experiment", in Proc. IPAC'23, Venezia. doi:10.18429/jacow-ipac2023-mopa110
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