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) OHiromi linuma (Ibaraki-Univ.), Satoshi Ohsawa, Hisayoshi Nakayama, Kazuro Furukawa (KEK), Shinji Ogawa (Kyushu-Univ.) and Ryota Matsushita (Univ. of Tokyo) 1. Physics goal: Explore the beyond standard model 2. Muon spin precession probes g-2 and EDM...catch the new physics! We measure $\vec{\omega}_a$ = Spin motion – cyclotron motion Assuming EDM upper limit ~ 1e-19 e.cm $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c$ 1mrad (0.006 degree) μ**φ** h h h μ μ w m j • Electric field \vec{E} = 0 *1: arXiv:2308.06230v1 [hep-ex] 11 Aug 2023 $\vec{\omega}_{SPIN} = \frac{e}{m} \frac{g-2}{2} \vec{B} + \frac{2c}{\hbar} \eta_{EDM} (\vec{\beta} \times \vec{B})$ $a_{\mu}(Exp) = 116 592 059(22) \times 10^{-11} (0.19 ppm) (*1),$ ◆Store muon beam in the uniform magnetic field (<0.1ppm) **EDM** ◆ Very precise control of the muon storage orbit $5-\sigma$ discrepancy from the SM. igoplusAngle between $\vec{\omega}_a$ and magnetic field \vec{B} is estimated to be 1mrad g-2 EDM Non-zero observation = new physics assuming EDM upper limit from the previous experiment. Standard Model expects ~ 2 x 10⁻³⁸ e · cm ◆If we measure such angle with 0.01mrad precision, we perform very Upper limit (E821) $< 1.9 \times 10^{-19} \, e \cdot cm (90\% \, CL)$ precise EDM measurement with 100 better sensitivity than previous exp. E821@BNL, Phys. Rev. D 80, 052008, 2009 Super precise adjustment for muon storage magnetic field is a KEY g-2:0.45ppm (statistical uncertainty) Goal: (2023-E989 0.20ppm (*1)) Typical size of circumference EDM sensitivity:1.5 x 10⁻²¹ e.cm image at J-PARC MLF length of storage ring: 3km(KEKB) ~ 27km(LHC) 3. Compact storage ring applying medical MRI type superconducting magnet Muon g-2 BNL, FNAL: 44m (D=14m) Reference [3] technology, requires newly developing 3-D spiral injection scheme! J-PARC:2.1m (D=0.7m) Reference [4] Mission of the beam transport line: Expect to perform +/-0.1ppm of high uniformity of three Tesla magnetic field Beam transport line . ➡Utilize fringe field 1. Transport muon beam from the exit of the muon LINAC to the Radial field B. injection point of the storage magnet Magnetic field of 3T, 3-D spiral injection (side view) deflects beam $ullet B_{
m R}$ direction and 300MeV/c muon beam 2. Apply appropriate "X-Y coupling" for "3-D spiral beam Beam channel in th Beam injection → Diameter of storage changes θ injection" orbit *is only 0.66m*. 3. Control injection angle (beam line slope of 26 degree) Superconducting coils After the kick **Beauties:** (Five thick ◆ Smooth connection between injection and storage sections without any sources of error field coils) A unit of magnet does work for this method and decrease sources of error field field beam $\gamma=3$ 4. Beam monitor inside the storage magnet: How do we control the beam? 2-D orbit Fiducial Storage orbit plane volume (1) Active Shield Steering Magnet: 弱収束磁場により、္ 250 運動エネルギー Control beam position/pitch 鉛直方向ベータト Vertical kick 4 Stored beam angle at z~0.95m Vertical kick \ ロン振動 monitor: detect vertical beam motion 0.8-3Beam position/profile monitor Green |z|<30mm[®] 3-D spiral trajectory 0.04-0.03-0.02-0.01 0 0.01 0.02 0.03 0.04 **2** Pulse Kicker Red|z|<100mm 10mm-0.4mrad Target:n=1.5E-4 0.2 $I_0 sin\left(\frac{\pi}{T_{\nu}}(t-t0)\right), : (t-t_0) < T_K$ ⑤ Pillar scintillator detector: detect time stamp $\times halfsinrac{2\pi}{T_{kick}}(t-t_0)$ 0,: $(t-t_0) > T_K$ Effective radial kicker field of muon decay $=B_{R0}(r,z) + B_R(z)sin\frac{2\pi}{T_{kick}}(t-t_0)$ Silicon detector Half-sin shape ₈₀ trajectory current for Half-sine shaped Kicker field × 10 $-0.3_{-0.2}^{-0.3}_{-0.1}^{-0.1}_{0} \xrightarrow{0.1}^{0.1}_{0.2}^{0.1}_{0.3}^{0.2}_{0.3}^{0.1}^{0}$ **Vertical kick** kicker current $2B_R>0$ (shape only) Reconstruct 600ns after injection "Good" injection $B_R = -n^{\frac{1}{2}}$ z-z' time $1B_R < 0$ MC truth snap by use red: Kicker field $B_{p}(z, t, R)$ of 4 & 5 Blue: Static radial field $B_z = B_{0z} | 1 - n \frac{r}{m}$ Gray: Effective radial field injection /5.6.3.3.1_{0.0.6.3}.3.4_{0.55}-0.4-0.3-0.2-0.1 0 0.1 0.2 0.3 0.4 0.5 **Y[m] x[m]** Weak Focus both direction Reference [5] Vertical [cm] 0<n<1: focus radially and vertically Vertical position(mm) VBO amplitude [m] 5. Development for 3-D spiral injection scheme by use of 80 keV electron gun preparation-1:X-Ycouplued beam by rotating Quads. preparation-2:kicker and "simple SiFi monitor" install **SiFi = Sintillating fiber** Kicker coil Detect "failed" beam **Rotating Quads for Detect stored beam** X-Y coupling Monitors' image 12 cm | 12 cm 2022/Mar. **Upperloss** パルス 電流源 15 cm 17 cm Non-coupled X-Y coupled DCビームチョッパーで **Lower Loss** Matsushita 径方向パル ス磁場B_k(t) 100nsec幅に切り出し Each data has <x2>, <y2>,<xy> Upper and lower coils with opposite **Lower Loss** Non-coupled X-Y coupled X-Y coupling control by use of three rotating quadrupoles is the key for 3-D spiral injection pulse current create pulse radial field Kicker ☐ Q-scan by use of single quadrupole (Q1 or Q2 or Q3) Kicker Current current by ☐ Change K-vale of Q1 (or Q2 or Q3) to measure focus and defocus beam shape 100nsec pulse Stored beam signal (~500nsec) Rogowski coil \square Reconstruct σ_0 (at initial point) **Estimate** σ_1 at the end of the transport line $\sigma_1 = M\sigma_0(M)^t$ Q-scan can Very preliminary measure Q-scan by use of three quads. Funny time dependent signals are detected...what happed!? 0 degree Stored beam detected by scintillating X-Y coupling 135 degree 180 degree component fiber monitor. Injected beam of 100ns Vertical scan 男ょつらいよ 50 width, and stored beam signal continues K~70 K~90 K~20 CHEME more than 500ns! 20 different Q settings for σ_0 measurement \Rightarrow $| \Leftrightarrow$ Reflected beam by kicker/fringe field hits 135 degree lower loss monitor set in the bottom Every set-up has different m₁₁~m₄₄ and Horizontal scan three measurements:<x2>,<y2> and <xy> Copper Time [s] ☐ At least four independent set-up data can solve 10 unknown preparation-3: "lyre shaped SiFi monitor" install parameters, in principle. **Expected signals from new monitor** Q-scan data is a kind of special data set Expected eccenric trajectory for a single particle (simulation 3-D spiral beam and new monitor image Fiber at r = 11, 11.5, 12.5, 13 cm
$$\begin{split} \langle x^2 \rangle_1 &= m_{11}^1 m_{11}^1 \langle x^2 \rangle_i + 2 m_{11}^1 m_{12}^1 \langle xx' \rangle_i + m_{12}^1 m_{12}^1 \langle x'x' \rangle_i \\ \langle y^2 \rangle_1 &= m_{33}^1 m_{33}^1 \langle y^2 \rangle_i + 2 m_{33}^1 m_{34}^1 \langle yy' \rangle_i + m_{34}^1 m_{34}^1 \langle y'y' \rangle_i \\ \langle xy \rangle_1 &= m_{11}^1 m_{33}^1 \langle xy \rangle_i + m_{11}^1 m_{34}^1 \langle xy' \rangle_i + m_{12}^1 m_{33}^1 \langle x'y \rangle_i + m_{12}^1 m_{34}^1 \langle x'y' \rangle_i \end{split}$$
 $x_f = m_{11} x_i + m_{12} x'_i$ 3 data for $y_f = m_{33} y_i + m_{34} y'_i$ each set-up $\langle xy \rangle_f = m_{11} m_{33} \langle xy \rangle_i + m_{11} m_{34} \langle xy' \rangle_i$ $\langle xy \rangle_{20} = m_{11}^{20} m_{33}^{20} \langle xy \rangle_i + m_{11}^{20} m_{34}^{20} \langle xy' \rangle_i + m_{12}^{20} m_{33}^{20} \langle x'y \rangle_i + m_{12}^{20} m_{34}^{20} \langle x'y' \rangle_i$ 150mm $+ m_{12} m_{33} \langle x'y \rangle_i + m_{12} m_{34} \langle x'y' \rangle_i,$ $10 \times 1 \left[\langle x^2 \rangle_i \right]$ Beam will hit Six $\langle xy \rangle \quad \langle xy' \rangle \setminus$ $(3*N) \times 1$ $X = TX_0$ fibers in order. $\langle xx' \rangle \quad \langle x'^2 \rangle$ $\langle x'y \rangle \quad \langle x'y' \rangle$ (Ex. N=20) $\langle xx'\rangle$ $\lceil \langle x^2 \rangle_1$ $(3*N) \times 10$ $\langle xy' \rangle \quad \langle x'y' \rangle \quad \langle yy' \rangle \quad \langle y'^2 \rangle$ $m_{12}^1 m_{12}^1 \quad 2m_{11}^1 m_{12}^1$ $\langle xy \rangle_1$ $\sqrt{\langle x^2 \rangle \langle p_x^2 \rangle} - \langle x p_x \rangle^2$ Summary and Future $\langle yy' \rangle$ $\langle x^2 \rangle_2$ Preparation for a new precise experiment for muon g-2 and EDM (E34) is ongoing. We expect the first beam in FY2028. $\langle xy \rangle_i$ C=determinant of σ $\lfloor \langle xy \rangle_{20}$ • 3-dimensional spiral injection is a key for new experiment, and feasibility studies shown here. $\langle xy' \rangle$ $t = \frac{\varepsilon_{x}\varepsilon_{y}}{\sqrt{C}} - 1$ • X-Y coupled beam is controlled by rotating quadrupole magnets. Q-scan and sigma-matrix measurements are introduced. $\langle x'y\rangle_i$ $X_0 = [T^t T]^{-1} T^t X$ Stored beam guided by kicker is detected. New lyre shape SiFi monitor will strong tool to understand "eccentric trajectory" t>1 Huge X-Y coupling $\langle x'y'\rangle_{i}$ We can get initial beam σ-matrix from beam Feasibility study goes well and many knowledge will be reflected on the new J-PARC E34. t~0.1 enough small x-y shape at copper position, in principle References Contact: Hiromi.linuma.spin@vc.ibaraki.ac.jp [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. 茨城大学 Ibaraki University Homepage: [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. http://muonspin.sci.ibaraki.ac.jp/ https://www.pasj.jp/web_publish/pasj2022/ proceedings/PDF/TUP0/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, https://g-2.kek.jp/

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