ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA118

DEMONSTRATION OF THREE-DIMENSIONAL SPIRAL INJECTION FOR THE J-PARC MUON g-2/EDM EXPERIMENT *

R. Matsushita†, The University of Tokyo, Bunkyo-ku, Japan
H. Iinuma, K. Oda, Ibaraki University, Mito, Japan
S. Ohsawa, H. Nakayama, M. A. Rehman, K. Furukawa, N. Saito. T. Mibe
High Energy Accelerator Research Organization, Tsukuba, Japan
S. Ogawa, Kyushu University, 812-8581, Fukuoka, Japan

Abstract

In the J-PARC Muon g-2/EDM experiment, to measure muon anomalous magnetic moment (g-2) and electrical dipole moment (EDM), it is necessary to accumulate 300 MeV/c muon beams with a 66 cm diameter region with a 3 T solenoid-type magnetic field. A new three-dimensional spiral injection scheme has been invented to achieve this target. Since this is the first instance to employ this injection scheme, a scale-down experiment with an electron beam of 297 keV/c and storage beam diameter of 24 cm is established at KEK. A simplified storage beam monitor using scintillating fiber has been designed and fabricated to measure the stored beam.

The 100 ns width pulsed beam is injected and the signal maintains a few microseconds by the stored beam observed. According to this result, the beam storage is confirmed. The recent result implies that the stored beam deviated from the design orbit and caused betatron oscillations. To measure the beam deviation quantitatively and tune the beam, the storage monitor has been updated. The data from this stored beam monitor are the primary data for considering the conceptual design of the beam monitor for the muon g-2/EDM experiment. This poster will discuss the measurement of beam storage by three-dimensional spiral injection and beam tuning using a scintillating fiber monitor.

INTRODUCTION

J-PARC muon g-2/EDM Experiment

The muon anomalous magnetic moment (g-2) is one of the physical quantities for which large discrepancies between predictions by the Standard Model of particle physics and experimental measurements have been reported [1]. In addition, the electric dipole moment (EDM) of elementary particles is greatly suppressed in the Standard Model, with values $O(10^{-42})$ $e \cdot$ cm. If EDM with larger values is observed, it will be evidence of CP-violation in the lepton sector. The J-PARC muon g-2/EDM experiment (E34) [2] aims to verify the muon g-2 anomaly and to search for muon EDM, and preparations are underway to start physics data-taking in JFY2028 to perform simultaneous measurements with a precision of 450 ppb for g-2 and 1.5×10^{-21} $e \cdot$ cm (90%C.L.) for EDM, respectively.

* This work is supported by JSPS KAKENHI Grant Numbers 19H00673, 26287055, 23740216, 22K14061.
† matsur@post.kek.jp

Demonstration Experiment of Three-Dimensional Spiral Injection

In the E34 experiment, a muon beam of 300 MeV/c must be injected and stored in a solenoid magnetic field of 3 T. The beam storage region, which is designed to have a magnetic field uniformity of less than 0.1 ppm to surpress g-2 systematic uncertainty has a diameter of 66 cm, and a brand new method, three-dimensional spiral injection [3], will be employed to achieve beam storage in such a compact region. In this technique, the beam is injected in a solenoidal magnetic field and applying vertical kick by the pulsed magnetic field of the kicker system, able to accumulate the beam in a weak focusing magnetic field.

Since this method is the first attempt in the world, a demonstration beamline has been constructed at KEK [4, 5]. Figure 1 shows an overview of the experimental beamline. This demonstration experiment uses electron beams. Both the beam momentum and the storage solenoid field strength are scaled down from the E34: 297 keV/c and 82.5×10^{-4} T, respectively. Under these conditions, the cyclotron radius is 12 cm and cyclotron period is 5 ns. The beam storage region has a weak focusing magnetic field as in E34, and it n-value is $n = 1.8 \times 10^{-2}$, two orders of magnitude stronger than E34 for easier beam accumulation.

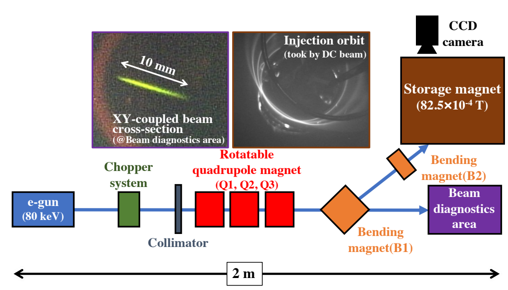

Figure 1: An overview of the demonstration beamline. The DC beam generated by the electron gun can be switched by the chopper system to a pulsed beam with a pulse width of 100 ns and a repetition rate < 50 Hz variable. The beam phase space is adjusted by three rotatable quadrupole magnets (Q1, Q2, Q3) to make an XY-coupled beam suitable for injection [6]. The beam is deflected by the bending magnets (B1, B2) and injected into the storage magnet from bottom of the storage magnet. The kicker system is installed in the storage magnet. In the beam diagnostics area, beam diagnostics can be performed by measuring the DC beam cross-section.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA118

CONFIRMING BEAM ACCUMULATION

A single scintillation fiber (Sci-Fi) shown in Fig.2 is installed inside the storage magnet to confirm the beam accumulation by measuring the signal from stores electrons.

Here, a cylindrical coordinate system (R, θ, z) is used to explain the geometrical relationship inside the storage chamber, where R is the distance from the center of the solenoid magnetic field, θ is the azimuthal angle, and z is the position along the solenoid axis. $z = 0$ cm is the storage plane.

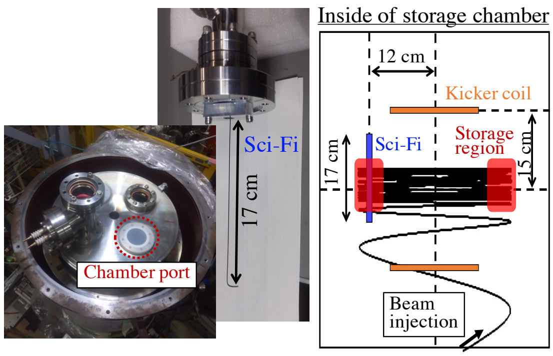

Figure 2: Left: The chamber port at the top of the storage chamber and single Sci-Fi using measurement. Right: Measurement setup. Sci-Fi was inserted into the beam storage region through the port at the top of the vacuum chamber, $R = 12$ cm axis.

To allow measurement by changing the Sci-Fi position in the R-direction, a rotary inductor was installed at the center of the port, and the Sci-Fi was attached to the tip of it with an offset of 3 mm from the rotation axis. The z-direction length of Sci-Fi ($-8.5\,\text{cm} \le z \le +8.5\,\text{cm}$) is sufficiently longer than the range of the beam storage region ($-6\,\text{cm} \le z \le +6\,\text{cm}$) determined by the weak focusing magnetic field. So, the betatron oscillation in the z-direction does not effect the measured signal.

The signal shown on the left of Fig.3 is one of the measurement results. The stored beam-derived signal fluctuates over time. This time fluctuation can be derived from the R-directional oscillation of the stored beam. If a beam is accumulated with an R-directional deviation from the designed orbit, it causes eccentric motion due to the distribution of the magnetic field in the storage region, and it generates oscillation in the R-direction.

STORAGE BEAM MONITOR

Measurement results indicate that the center of the stored beam is estimated to be in eccentric motion. This eccentric motion broadens the R-directional distribution of the stored beam and also causes time fluctuation. The stored beam shifts from the designed orbit causing this motion. A storage beam monitor to measure the R-directional distribution of the stored beam and to adjust the beam based on the measurement results is discussed.

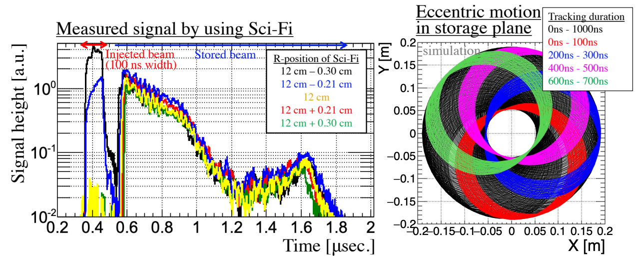

Figure 3: Left: Measured signals. Injected 100 ns width pulsed beam and applied kick in this measurement. Signal from injected beam observed < 0.5 μs and stored beam observed > 0.5 μs. The signal from the stored beam has time fluctuation. Right: The image of the eccentric motion of the stored beam. Horizontal- and Vertical-axis means position on the storage plane and $(X, Y) = (0, 0)$ means center of the solenoid field. This eccentric motion induces fluctuation of the measured signal.

Conceptual Design

The conceptual design of the storage beam monitor is shown in Fig.4.

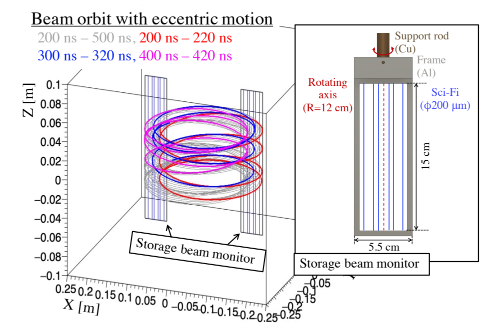

Figure 4: Eccentric motion and storage beam monitor. Stored beams are detected by aligning Sci-Fis with a diameter of 200 μm in the R-direction. Sci-Fis are placed at $R = 12\,\text{cm} \pm 0.5\,\text{cm}$, $12\,\text{cm} \pm 1\,\text{cm}$, $12\,\text{cm} \pm 2\,\text{cm}$, respectively. This beam monitors will be installed at two azimuth angles, $\theta = \pm\frac{\pi}{2}$ rad.

The storage beam monitor detects the beam using six Sci-Fi arrays in the R-direction. To reduce the effect on the stored beam, Sci-Fi with a diameter of 200 μm is used and sparsely aligned in the R-direction. In order to perform the measurement while a kicker device (current peak: 45 A, duration: 140 ns) is operating nearby, the light signal from each Sci-Fi is transmitted by optical fiber to a location far enough outside the vacuum chamber and converted into an electrical signal using a photodetector. Since what we want to measure in this beam monitor is the signal derived from the radial oscillation of the stored beam, the z-directional length of each Sci-Fi is set to $-7.5\,\text{cm} \le z \le +7.5\,\text{cm}$, which sufficiently covers the z-directional range of the beam storage area determined from the weak focusing magnetic field. The beam monitor is mounted on a copper support rod that is connected to the rotary induction motor at the top of

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA118

the vacuum chamber. Then, the entire storage beam monitor can be rotated with the port center $R = 12$ cm as the rotation axis, which makes it possible to measure with a narrower Sci-Fi spacing in practice.

This storage beam monitor will be installed at two azimuth angles, $\theta = \pm\frac{\pi}{2}$ rad. If the stored beam is in eccentric motion, the betatron tune in the R-direction is $\sqrt{1-n} \simeq 0.99$, so that oscillations in opposite phases can be observed at two beam monitors 180 deg apart in the azimuth position, as shown in Fig. 5.

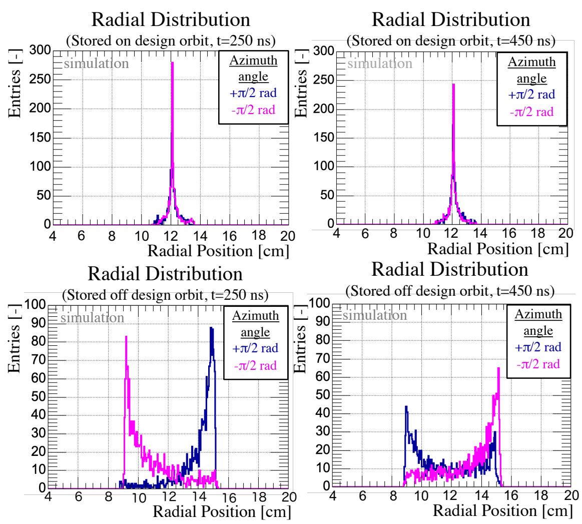

Figure 5: Radial distribution of stored beam with time. Upper row: assuming accumulation on design orbit. Lower row: assuming accumulation 3 cm off design orbit in R-direction. Colors represent the azimuthal position. The distribution is stable in case of accumulation on design orbit, but off design orbit leads to time fluctuations due to eccentric motion, and the time fluctuates in the opposite phase at 180 deg away in the azimuthal position.

Simulation Study

Simulations were performed to confirm whether storage beam monitor measurements could be used for beam tuning. In this simulation, a particle distribution with a phase space suitable for injection (so-called XY-coupled beam) was injected along a reference trajectory, and the hit timing distribution to Sci-Fi at each position was confirmed from the motion of the stored particles, which was used as the expected signal of the measurement. In this case, the effect of decreasing stored beam particles due to multiple scattering is not taken into account. Both cases where the beam accumulates on the design orbit and off the design orbit were performed.

Figure 6 shows the expected signals, where the left represents beam accumulation on the design orbit, and the right represents accumulation 3 cm off the design orbit in the R-direction. When the beam is accumulated on the design orbit, the distribution is localized at $R = 12$ cm, and the amount of Sci-Fi signals inside the beam monitor is larger than that outside. On the other hand, when the beam is accumulated with a shift of 3 cm in the R-direction. The Sci-Fi signal inside the beam monitor is reduced and the signal outside is increased because the distribution spreads in the R-direction and the number of particles near the design orbit decreases.

According to this result, it is possible to put the stored beam into the design orbit by adjusting the beam so that (*Amount of inner Sci-Fi signals*)/(*Amount of outer Sci-Fi signals*) becomes larger. In our case, the adjustment knob is the beam direction at the injection point, and the two magnets installed just before the injection are used to adjust the beam in both the x- and y-directions.

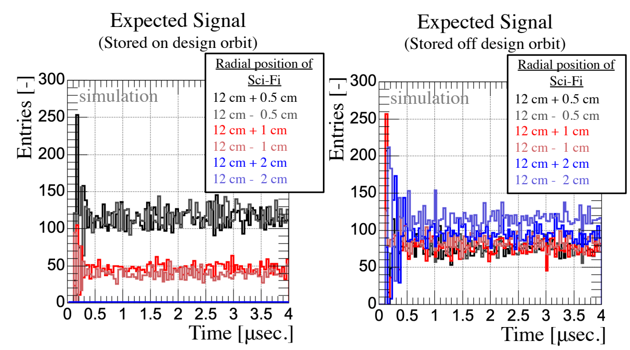

Figure 6: Expected signal of storage beam monitor. The left figure shows the case where the beam is stored on the design orbit, and the right figure shows the case where the beam is stored 3 cm off the design orbit in the R-direction. The color difference means each Sci-Fi positions.

CONCLUSION

In the demonstration experiment of three-dimensional spiral injection beam accumulation was successfully confirmed by measurement using Sci-Fi. From the measurement results, it was estimated that the accumulated beams in eccentric motion because the beams were accumulated with a deviation from the designed orbit. In order to solve this eccentricity, a beam monitor using some Sci-Fis was studied to measure the R-distribution of the stored beam and to adjust the beam. Simulation studies have shown that the storage beam monitor can be used to adjust the beam. This beam monitor is now under fabrication and will be installed in the first half of this fiscal year.

ACKNOWLEDGEMENTS

The author thanks H. Hisamatsu, H. Someya, T. Suwada and Y. Yano for their general support. And this study is supported by the Mechanical Engineering Center of KEK Applied Research Laboratory.

REFERENCES

[1] T. Albahri *et al.* (Muon $g-2$ Collaboration), "Measurement of the anomalous precession frequency of the muon in the

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA118

Fermilab Muon $g-2$ Experiment,"*Phys. Rev. D*, vol. 103, p. 072002, Apr. 2021. doi:10.1103/PhysRevD.103.072002

[2] M. Abe *et al.*, "A New Approach for Measuring the Muon Anomalous Magnetic Moment and Electric Dipole Moment", *Prog. Theor. Exp. Phys.*, vol. 2019, no. 5, May 2019. doi:10.1093/ptep/ptz030

[3] H. Iinuma *et al.*, "Three-dimensional spiral injection scheme for the $g-2$/EDM experiment at J-PARC,"*Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 832, pp. 51–62, 2016. doi:10.1016/j.nima.2016.05.126

[4] M. A. Rehman, "A Validation Study on the Novel Three-Dimensional Spiral Injection Scheme with the Electron Beam for Muon $g-2$/EDM Experiment,"Ph.D.thesis, SOKENDAI, Japan, 2020. http://id.nii.ac.jp/1013/00006023/

[5] R. Matsushita *et al.*, "Development of Pulsed Beam System for the Three Dimensional Spiral Injection Scheme in the J-PARC muon g-2/EDM Experiment", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 809–812. doi:10.18429/JACoW-IPAC2021-MOPAB256

[6] M. A. Rehman *et al.*, "The First Trial of XY-Coupled Beam Phase Space Matching for Three-Dimensional Spiral Injection", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 553–556. doi:10.18429/JACoW-IPAC2021-MOPAB162