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BEAM CONTROL AND MONITORS FOR THE SPIRAL INJECTION TEST EXPERIMENT*

M. A. Rehman†, SOKENDAI (The Graduate University for Advanced Studies), Kanagawa 240-0193, Japan
H. Iinuma, Ibaraki University, Mito, Ibaraki, Japan
S. Ohsawa, H. Nakayama, K. Furukawa, T. Mibe, H. Hisamatsu, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

A new experiment at J-PARC (E34) is under construction to measure the muon's g-2to unprecedented precision of 0.1 ppm and electric dipole moment up to the sensitivity of 10^{-21} e-cm in order to explore new physics beyond the standard model. A novel three-dimensional spiral injection scheme has been devised to inject and store the beam into a small diameter MRI-type storage magnet for E34. The new injection scheme features smooth injection with high storage efficiency for the compact magnet. However, spiral injection scheme is an unproven idea, therefore, a Spiral Injection Test Experiment (SITE) at KEK Tsukuba Campus is underway to establish this injection scheme. SITE consists of a 80 keV thermionic electron gun, two-meter-long beamline, and a solenoid storage magnet. The DC electron beam spiral track has been confirmed by the de-excitation of the nitrogen gas in the vacuum chamber of the storage magnet. A new wire scanner system has been developed to extract the beam current, profile and geometrical information of three-dimensional trajectory.

INTRODUCTION

The most recent measurement of muon g-2 at BNL(E821) conclude a 3 σ [1] discrepancy with the equally precise standard model prediction. The new J-PARC muon g-2/EDM (E34) is under preparation to resolve this tantalizing discrepancy. The E34 experiment will employ a completely new approach in order to measure the muon's g-2. The final goal of E34 is to measure the muon's g-2 with a precision of 0.1 ppm and EDM down to the value of 10^{-21} e.cm [2].

In order to measure the muon g-2 a low emittance polarized muon beam will be stored in a precise magnetic field to measure the evolution of the spin precession vector with respect to time. In E34 a low emittance muon beam of momentum 300 MeV/c will be injected into a 3-T Magnetic Resonance Imaging (MRI) type solenoid magnet in order to store the muon beam on a 0.66 m diameter orbit. The MRI-type storage magnet will provide an unprecedented local field uniformity of 0.2 ppm. A new three-dimensional spiral injection scheme has been invented in order to inject the beam into the MRI-type magnet. This new injection scheme will enhance injection efficiency and overcome technical challenges related to the small storage orbit diameters. In the spiral injection scheme, the beam will be injected at the vertical angle into the storage magnet. The radial field of the solenoid will decrease the vertical angle of the beam as it approaches the mid plane of the magnet. Finally, a magnetic kicker will guide the beam to the storage volume where the beam will be stored under a weak focusing field [3–6].

The three-dimensional spiral injection scheme is an unprecedented injection idea, therefore, a demonstration experiment to establish the feasibility of this new injection scheme is necessary. A scale down Spiral Injection Test Experiment (SITE) with an electron beam is under development at KEK Tsukuba campus. This paper will describe the development of the wire scanner type monitors for the Spiral Injection Test Experiment.

SPIRAL INJECTION TEST EXPERIMENT (SITE)

The SITE setup is consists of a 2 m long straight beamline, a solenoid storage magnet to store the electron beam and a forty degree bend section to guide the electron beam towards the storage magnet. A triode type thermionic electron gun with LaB_6 cathode is used to generate the DC electron beam of 80 keV with the beam current in the range of a few μA. After the electron gun, a magnetic lens focuses the beam. A pair of steering coils also have been installed to control the transverse position of the beam. An electric chopper system after the electron gun produces a pulsed beam. Details of the electric chopper can be found in [7]. A collimator of diameter 3 mm and depth 5 mm is placed after the electric chopper. The collimator serves as the beam dump for the chopper system and also creates a differential vacuum system for the

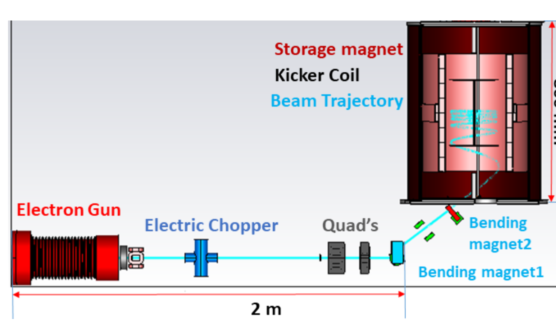

Figure 1: The side view of the 3D model of Spiral Injection test Experiment.

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† rehman@post.kek.jp

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gas monitor in the storage magnet. After the collimator, two normal quadrupole magnets control the beam phase space for the spiral injection. Due to the radial fringe field of the storage magnet, an XY-coupled beam at the injection point is required to avoid beam de-focusing. In order to apply the XY-coupling rotated quadrupole magnets are in preparation.

The first bending magnet 1 is placed on the straight beamline to deflect the beam forty degree towards the storage magnet. A second bending magnet 2 near the injection point controls the final injection angle.

The storage magnet consists of a 540 mm long solenoid coil. The solenoid coil is enclosed in the iron yoke. An auxiliary coil was placed at the center of the solenoid in order to produce a weak focusing field at the center of the storage magnet [8]. The pulsed magnetic kicker also under development will keep the beam to the center of the storage magnet [9]. The layout of the SITE experimental setup is shown in Fig. 1. A new wire scanner monitor for the beam profile measurement was developed for the solenoid storage magnet. The details will be discussed in the forthcoming section. A comparison of parameters between E34 and SITE is given in Table 1.

Table 1: Comparison of Parameters between E34 and SITE

Parameters	E34	SITE
Magnetic field strength	3 T	0.0082 T
Momentum	300 MeV/c	296 keV/c
Cyclotron Period	7.4 ns	5 ns
Storage orbit diameter	0.66 m	0.24 m

BEAM MONITORS FOR THE SOLENOID STORAGE MAGNET

Two kinds of monitors have been used to diagnose the beam inside the storage magnet. First, we used a non-destructive gas monitor to confirm the beam inside the storage magnet. Secondly, new wire scanner type monitors have been developed to measure the beam profile.

Gas Monitor

In order to observe the electron beam as fluorescent light, the vacuum chamber of the storage magnet was filled with the nitrogen gas. When the electron beam collides with the nitrogen gas, some molecules are ionized and some undergo the excitation. The de-excitation of nitrogen molecules results in the emission of fluorescent light in the visible wavelength of the range (390 nm $< \lambda <$ 470 nm). A CCD-camera is used to observe fluorescence light from the de-excitation. Figure 2 shows a typical beam injected into the storage magnet. The gas monitor is an efficient way to confirm beam inside the storage magnet, but it cannot provide the beam size information. Therefore, the wire scanner beam profile monitor was developed.

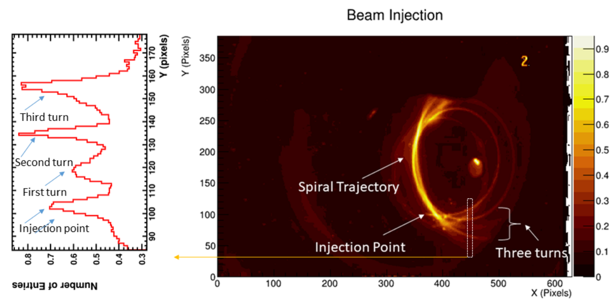

Figure 2: Electron beam track in the vacuum chamber of the storage magnet is visible due to the de-excitation of the nitrogen gas. Three turns can be seen clearly from 1D histogram of CCD-camera photo.

Wire Scanner

The wire scanner monitor was developed to measure the beam profile in the storage magnet. In the wire scanner type monitors, the beam hits the wire and deposits energy into the wire and charges converted to a corresponding current. The voltage across a resistor is proportional to instantaneous current absorbed in the wire. In order to measure the vertical beam profile inside the storage magnet, horizontal wires are moved vertically to measure the beam current at each position.

The wire scanner is consists of a copper wire of 1 mm diameter and a driving system to scan the copper wire through the beam. The driving system is composed of a linear feedthrough and linear actuator [10]. Two wire scanners

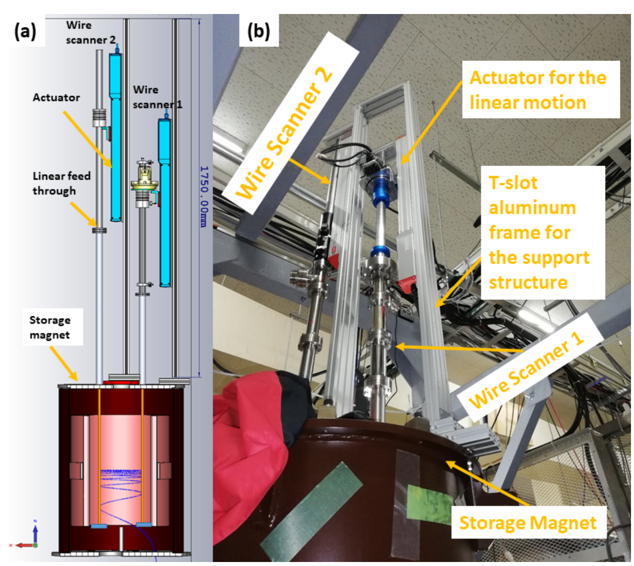

Figure 3: (a) Schematic of two wire scanner setup. (b) Wire scanner system on the top of the storage magnet.

were installed on the storage magnet in order to measure the beam profile and beam evolution in the storage magnet. The wire scanner 1 was installed at 2 cm away from the injection point and wire scanner 2 was placed at 180 degrees away from the wire scanner 1 for the beam profile measurement at half cyclotron period. Figure 3 (a) shows the 3D model

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of the wire scanner set up and (b) is a photo of the wire scanner set up at the storage magnet. In the wire scanner, the copper wires were placed horizontally in order to measure the vertical beam profile. The horizontal wire is divided into the horizontal direction in order to measure the radial offset of the beam. A vertical wire on wire scanner 1 was also installed to measure the horizontal beam profile. The horizontal beam profile measurements are still in progress.

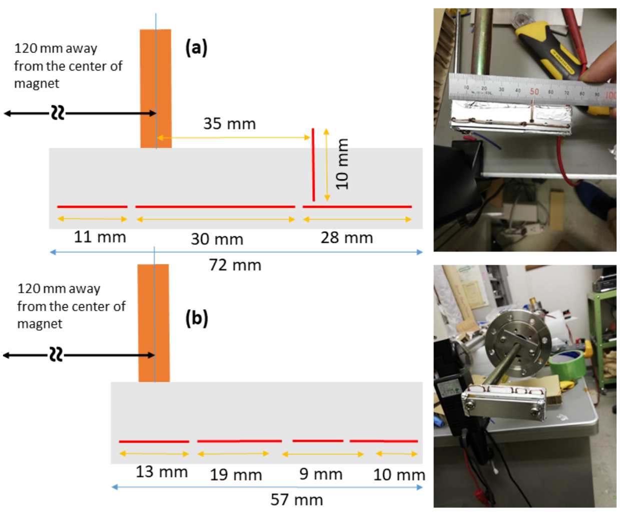

Figure 4: (a) Wire scanner 1 dimensions. The red lines are the wires. (b) Wire scanner 2 dimensions. Wire scanner 2 was placed 180 degrees away from the wire scanner 1.

RESULTS

The wire scanners were drive by linear actuator with a resolution of 1 mm. The signal from the wires was taken out of the vacuum chamber via vacuum feed-throughs and terminated into the 1 MΩ terminal of an oscilloscope. A C# program was developed to log the data and provide online plotting during the beam test.

In order to reduce the vertical de-focusing of the beam, two normal quadrupole magnets were installed on the injection beamline. A CST-PS [11] simulation has been carried out with the experimental conditions in order to estimate the vertical beam growth in the storage magnet. In the simulation the electron beam of energy 80 keV and current 20 µA was assumed. In the simulation, the beam emittance was 1 mm−mrad in horizontal and vertical (X-Y) planes and vertical focus beam is preferable for the injection. Figure 5 shows the CST-PS simulation results and left bottom plot shows injected beam dimensions. As the beam moves upward in the magnet the number of counts decrease, but the area under the curve remains the same.

During the beam tests, the energy of the electron beam was 80 keV with the beam current of 20 ± 1 µA (DC). The beam emittance is expected to be few mm-mrad but the detail number is still in study. Figure 6 shows the preliminary results of the wire scanner 1 and comparison with simulation. As the beam turns, the area which is indicated in the dashed line of Fig. 6 decrease down to 14% at 1st turns and 2% decrease at the 2nd turn. The results from the wire scanner 2 are still in progress. Due to the axial symmetric field of the storage magnet, an XY-coupled beam is required to reduce the de-focusing of the beam.

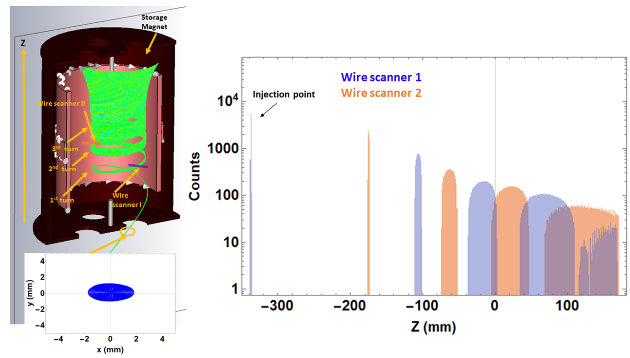

Figure 5: Left: CST-PS particle tracking simulation with the real experimental condition in the storage magnet. The bottom left plot shows the injected beam profile. Right: The vertical beam profile at wire scanner 1 and 2 position.

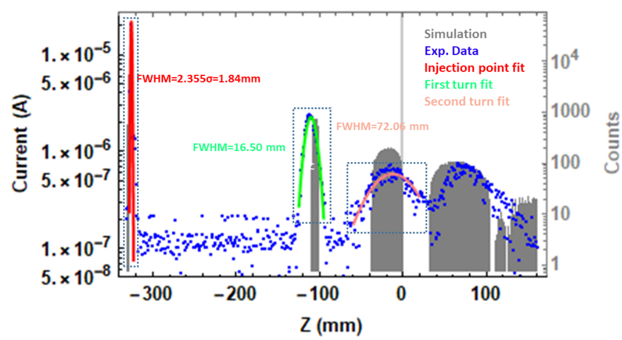

Figure 6: Vertical beam profile measurement from wire scanner 1 as a function of vertical position. The storage magnet center was defined as a reference point (Z = 0).

SUMMARY

A wire scanner type monitor was designed and constructed for the beam profile measurement in the solenoid type storage magnet at KEK. A beam test of the wire scanner monitor successfully has been carried out and preliminary results obtained. The preliminary data from the wire scanner is in good agreement with simulation results.

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REFERENCES

[1] G.W. Bennett *et al.*, "Final Report of the muon E821 anomalous magnetic moment measurement at BNL", *Phys. Rev.*

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D., vol. 73, p. 072003, 2006. doi:10.1103/PhysRevD.73.072003

[2] M. Aoki *et al*., "Conceptual Design Report for the Measurement of the Muon Anomalous Moment g-2 and Electric Dipole moment at J-PARC (2011)", unpublished.

[3] H. Iinuma *et al*., "Three-dimensional spiral injection scheme for the g-2/EDM experiment at J-PARC", *Nucl. Instr. Meth.*, vol. A832, pp. 51-62, 2016. doi:10.1016/j.nima.2016.05.126

[4] H. Iinuma *et al.*, "Three-Dimentional Spiral Beam Injection for a Compact Storage Ring", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1673–1676. doi:10.18429/JACoW-IPAC2018-TUPML060

[5] H. Iinuma *et al.*, "Development of three-dimensional spiral beam injection scheme with X–Y coupling beam for MRI sized compact storage ring", in *Proc. 15th Annual Meeting of Particle Accelerator Society of Japan (PASJ2018)* August 7-10, 2018, Nagaoka, Japan, paper WEOM07, pp. 79–83.

[6] M. A. Rehman *et al.*, "Progress of the Novel Three-dimensional Spiral Injection Scheme Test Experiment", in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 717–720. doi:10.18429/JACoW-LINAC2018-THPO017

[7] M. A. Rehman *et al.* "Development of the three-dimensional injection spiral injection by using electron beam for muon g-2 experiment", in *Proc. of 14th Annual Meeting of Particle Accelerator Society of Japan (PSAJ'17)*, Sapporo, Japan, Aug. 2017, paper WEOM01, pp. 114–117.

[8] M. A. Rehman *et al.*, "Test experiment of 3-D spiral injection scheme using electron beam for new g-2/edm experiment at J-PARC", in *Proc. of the 13th Annual Meeting of Particle Accelerator Society of Japan (PSAJ'16)*, Chiba, Japan, Aug. 2016, paper TUP056, pp. 1004–1007.

[9] M. A. Rehman *et al.*, "Development of the pulsed magnetic kicker for the spiral injection test experiment", *Proc. of 15th Annual Meeting of Particle Accelerator Society of Japan (PASJ2018)*, Nagaoka, Japan Aug. 2018, paper THP006, pp.768-772.

[10] THK, http://www.thk.com

[11] CST, http://www.cst.com

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