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PROGRESS OF THE NOVEL SPIRAL INJECTION TEST EXPERIMENT*

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Abstract

A new muon $g-2$/EDM experiment at J-PARC (E34) is under preparation in order to resolve a 3 σ discrepancy of muon anomalous magnetic dipole moment between the measurement and the standard model prediction. The E34 experiment will employ a unique three-dimensional spiral injection scheme in order to store the muon beam into a small storage orbit. In order to demonstrate the feasibility of this novel injection scheme, the Spiral Injection Test Experiment (SITE) with the electron beam is under construction at KEK Tsukuba campus. The goals of the SITE are divided into two phases. In the first phase of the SITE, 80 keV DC electron beam was injected and detected as a fluorescent light due to the de-excitation of the nitrogen gas into solenoidal storage magnet. In the second phase of the SITE, the pulsed electron beam, and a pulsed magnetic kicker are developed in order to keep the pulsed beam on the very midplane of the solenoidal storage magnet. This paper describes the achievements of the first phase of the SITE and progress towards the second phase.

INTRODUCTION

The muon's anomalous magnetic moment is one of most important measurement in elementary particle physics. The recent measurement of muon $g-2$ results 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 current discrepancy. The E34 experiment is aiming to measure muon's $g-2$ to the precision of 0.1 ppm and EDM down to the sensitivity of 10^{-21} e.cm [2].

The key idea to measure muon $g-2$ is to store polarized muon beam in a magnetic field and measure the evolution of spin precession vector with respect to time. In E34 a low emittance muon beam of momentum 300 MeV/c from muon accelerator will be injected into a 3-T Magnetic Resonance Imaging(MRI)-type solenoid magnet in order to store the muon beam in 0.66-m diameter orbit. In order to enhance injection efficiency and overcome technical challenges related to small storage orbit, a new three-dimensional spiral injection scheme is under development to inject the muon beam into MRI type storage magnet. Figure 1 shows the basic concept of a three-dimensional spiral injection scheme. The details and recent updates of three-dimensional spiral injection scheme can be found in [3–5].

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The three-dimensional spiral injection scheme is an unproven idea, therefore, a demonstration experiment to prove the feasibility of this unique scheme is inevitable. A scale down Spiral Injection Test Experiment (SITE) by the use of electron beam is under development at KEK Tsukuba campus. This paper will describe the development of the spiral injection scheme test experiment (SITE).

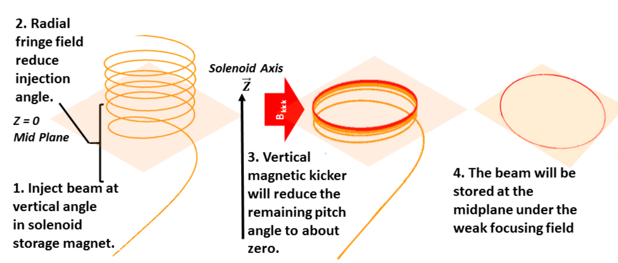

Figure 1: Layout of three-dimensional spiral injection scheme.

SPIRAL INJECTION TEST EXPERIMENT (SITE)

The SITE setup contains a 2 m long straight beamline, a solenoid storage magnet to store the electron beam and forty degrees 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 current in the range of few μA.

After the electron gun, a magnetic lens is placed to focus the low energy beam. A pair of steering coils also has been placed to control the transverse position of the beam. An electric chopper system has been placed after the electron gun to produce the pulsed beam. Details of the electric chopper can be found in [6]. A collimator of diameter 3 mm and depth 5 mm is placed after the electric chopper. The collimator is served as the beam dump for the chopper system and also used to create the differential vacuum system for the gas monitor in the storage magnet.

A bending magnet (BM1) is placed on the straight beamline to deflect the beam at forty degrees towards the storage magnet. A second bending magnet (BM2) is also placed near the injection point in order to control the injection angle slightly. Air core quadruple magnets have been placed on a bend section to create required beam phase space for the spiral injection.

A pulsed magnetic kicker is also under development in order to keep the beam to the very center of the storage

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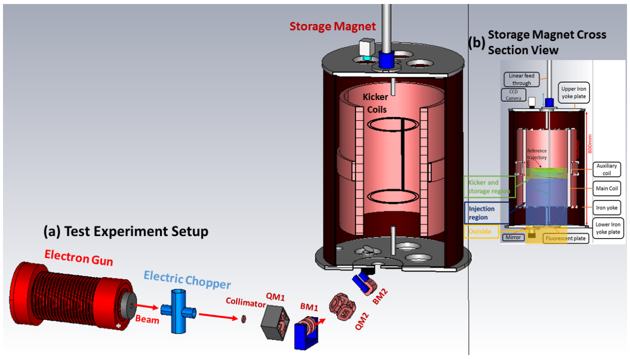

Figure 2: (a) A diagram showing the 3D schematic of spiral injection test experiment. (b) The schematic of the storage magnet with monitors and reference trajectory.

magnet. The kicker system for the SITE will be discussed in the forthcoming sections. The details about each device on the straight beamline of SITE can be found in [7]. The layout of the SITE experimental setup is shown in Fig. 2 (a). The schematic of the storage magnet with a reference trajectory and monitors are shown in Fig. 2 (b). A comparison of parameters between SITE and E34 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	0.296 keV/c
Cyclotron Period	7.4 ns	5 ns
Storage orbit diameter	0.66 m	0.24 m

In the first phase of the SITE, DC electron beam was detected as fluorescent light. In the SITE nitrogen gas monitor was used to detect the DC electron beam spiral track in the storage magnet's vacuum chamber. In the gas monitor, differential vacuum pumping has been employed to detect electron beam as a fluorescent light due to the nitrogen gas de-excitation along the beam path. The details of beam detection in the storage magnet can be found in [7].

BEAM PHASE SPACE FOR SPIRAL INJECTION

The radial fringe of the solenoid storage magnet requires a strongly XY-coupled beam. In Fig. 3 above four plots are showing the beam phase space at the matching point $Z = -500$ mm from the center of the storage magnet. The matching point lies outside of the storage magnet. Black points show the uncoupled beam (ideal parallel beam) and red points show the required coupled beam phase space. The bottom two plots in Fig. 3 shows the beam injection without (black) and with coupled (red) beam. In the Fig. 3 bottom left the beam start diverging vertically after $Z = -100$ mm in the case of non-coupled beam whereas in the case of appropriate coupled beam injection beam do not diverge completely at $Z = -100$ mm.

Air core quadrupole magnets have been mounted on the bend section in order to create required beam phase space. The details calculation of TWISS and coupling parameters can be found in [3].

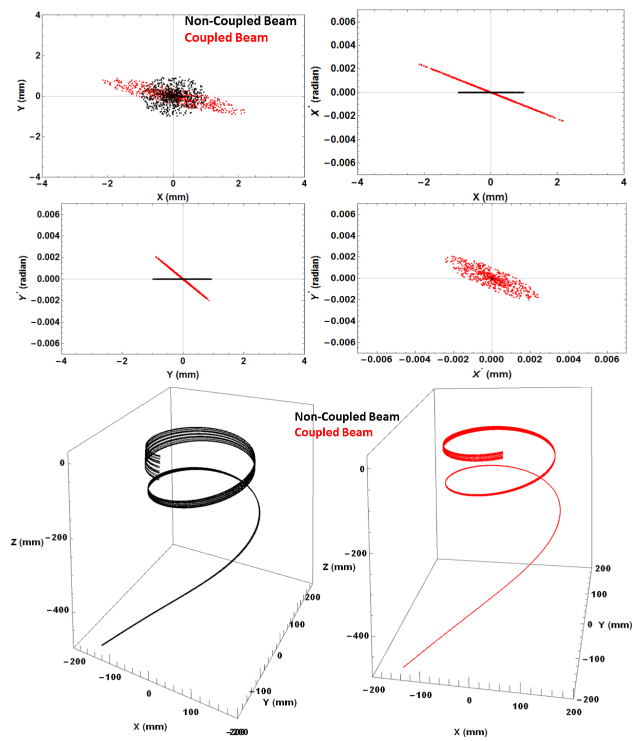

Figure 3: The above four plots are the required phase space at the matching point ($Z = -500$ mm). The black points show the beam phase space without coupling and red points show with coupling. Bottom two plots are showing the beam injection with and without coupled beam.

PULSED MAGNETIC KICKER

The pitch angle of the beam will be reduced to 0.018 rad due to the radial field of storage magnet at $Z = -100$ mm. At the $Z = -100$ mm, the vertical magnetic kicker will apply the kick to guide the beam to the very center of the storage magnet. The kicker field can be defined as follows

$$B_{kick} = B_{peak} Sin\left(\frac{2\pi}{T_{kick}} t\right) \tag{1}$$

where T_{kick} is the duration of the kick and B_{peak} represent the peak kicker field. The half sine shape has been considered for the kick, therefore, $T_{kick} = \frac{T}{2}$ and T is total time period.

After the kick, the beam will be stored under the weak focusing field. In the weak focusing field the beam motion will be oscillatory in the storage volume. The weak focusing magnetic field can be defined as follows

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$$B_z = B_0\left(1 - n\frac{\Delta r}{r} + n\frac{z^2}{2r^2}\right) \quad (2)$$

$$B_r = \left(-n\frac{z}{r}\right)B_0 \quad (3)$$

where $B_0(= 82.5$ Gauss) is the main solenoidal field at $r = 12$ cm, $z = 0$ cm and $\Delta r = r - r_0$. Here n is field index $\left(n = -\frac{r_0}{B_0}\frac{\partial B_z}{\partial r}\right)$. The radial and vertical focusing can be achieved if $n < 1$ and $n > 0$ respectively. Figure 4 is showing the magnetic field profile of the SITE storage magnet with the field index value of $n = 1 \times 10^{-3}$.

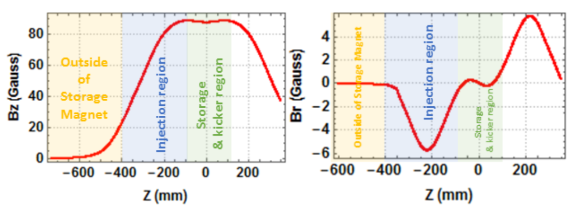

Figure 4: Left: Axial field profile of the storage magnet. Right: Radial field profile of the storage magnet with weak focusing index $n = 10^{-3}$.

Figure 5 (a) shows two kicker coil design for 2π and $\pi/6$ cases. In the 2π configuration of the kicker, the current in upper and lower coils are opposite to each other and they produced cylindrical symmetric radial field. The $\pi/6$ kicker design can be realized by the rectangular dipole coil. In the case of 2π kick shape the required kicker duration is $T_{kick} = 95/2$ and $B_{kick} = 70$ mG. In the case of $\pi/6$ kick shape the required kicker duration is $T_{kick} = 95/2$ and $B_{kick} \cong 1$ G.

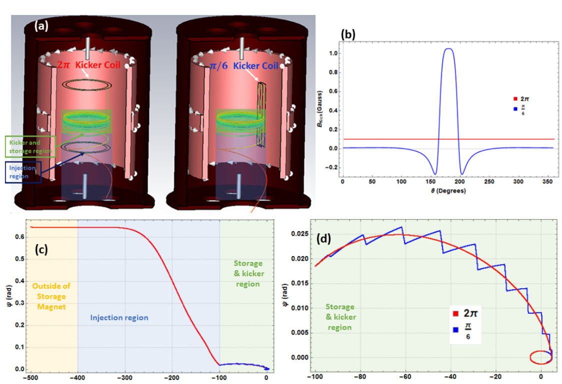

Figure 5: (a) Two models of the magnetic kicker. (b) Magnetic field profile for the 2π and $\pi/6$ kicker model. The required magnitude of magnetic field increase in the case of $\pi/6$ kicker model due to a limited region. (c) The pitch angle starting from the injection point to the storage region as a function of the vertical position (Z). (d) Pitch angle in the kicker and storage region.

Both types of kicker will be tested in SITE in order to find the best shape for the kicker. The bottom two plots in Fig. 5 shows the reduction of the pitch angle due to the kicker field (c) and storage of the beam in midplane (d).

The $\pi/6$ kicker coil shape has been optimized to reduce the inductance of coils. The optimization results in the coils of height 175 mm, width 62 mm and the gap between coils was 35 mm. The total inductance of optimized coils in series has been estimated at 0.8 µH by using CST [8]. Figure 6 left shows the optimized $\pi/6$ coil shape and right shows the magnetic field map in radial and vertical directions. The kicker coil excitation current was set to 10 A for the simulation. The details of the pulsed magnetic kicker can be found in [9].

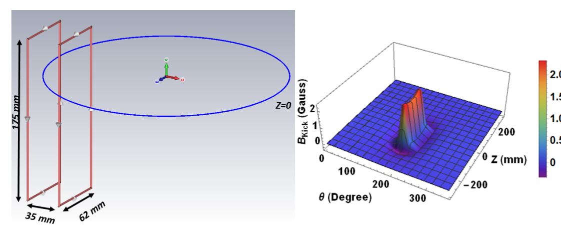

Figure 6: Left:Optimized $\pi/6$ kicker model. Right: Magnetic field map in radial and vertical directions. The exciting current of the coil was set to 10 A.

The pulsed current power supply for the magnetic kicker is also under development. The schematic of an electronic circuit for the current power supply is shown in Fig. 7.

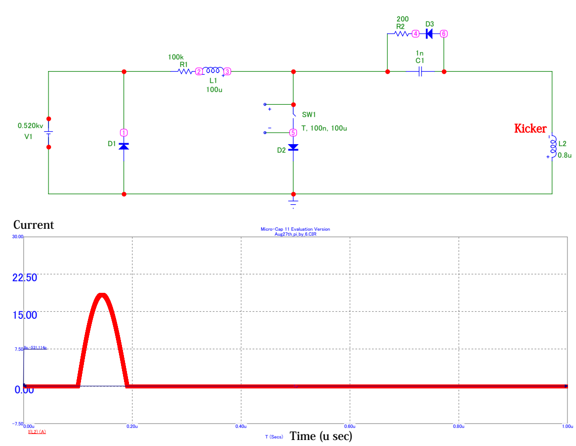

Figure 7: Top: The schematic electronic circuit for the pulsed magnetic kicker. Bottom: The pulsed current through kicker coil.

CONCLUSION

A new three-dimensional spiral injection is under development by using the electron beam in order to realize new J-PARC's muon $g-2$/EDM experiment. An electron beamline and storage magnet has been constructed for the SITE. The electron beam in the storage magnet was confirmed as fluorescent light due to the de-excitation of nitrogen gas in the storage magnet. The required beam phase space for the spiral injection has been calculated. A pulsed magnetic

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kicker and the power supply is under development to guide the pulsed beam at the midplane of the storage magnet. Particle tracking studies have been carried out with the different shapes of the kicker in the kicker and weak focusing field in order to find the appropriate magnetic field and time period for a kicker.

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