

THREE-DIMENSIONAL SPIRAL BEAM INJECTION FOR A COMPACT STORAGE RING

H. Iinuma*, Ibaraki University, Mito, Ibaraki, Japan

K. Furukawa, H. Hisamatsu, H. Nakayama, S. Ohsawa, K. Oide, K. Sasaki, Y. Fukao, T. Mibe,
KEK, Tsukuba, Ibaraki, Japan

M. A. Rehman, SOKENDAI, Tsukuba, Ibaraki, Japan

Abstract

A newly developing three-dimensional spiral injection scheme for the beam insertion into a compact (medical MRI size) ring is introduced. The new scheme provides a smooth injection utilizing a radial solenoidal fringe field. To meet the requirements from physics goal, we remove any device, which causes the electric field in this injection scheme. In this paper, we will discuss the outline of the new injection scheme, emphasizing an importance of a so-called X - Y coupling in the beam phase space. Status of a test bench works to demonstrates feasibility of this injection scheme will also be discussed.

INTRODUCTION

A new precise measurement of the muon's anomalous magnetic moment ($g-2$) and its electric dipole moment (EDM) is in preparation at J-PARC muon facility. In order to measure a precession of the spin relative to the velocity at the better accuracy than ever, we have designed a conceptually new experiment separately from the conventional method of the former $g-2$ experiments [1] and ongoing experiment at FNAL [2]. A compact storage ring, such as medical MRI size, allow us to achieve a perfect adjustment for the magnetic field locally. A volume of a detector, lying inside the muon storage ring, also becomes compact and is suitable for a decay positron (e^+) tracking event-by-event. Measuring positron momentum vector at a decay point is a key to measure the spin precession, because a decay positron tends to be emitted along the spin vector of the muon according to the V-A theory. In case of a nonzero EDM, a precession of the spin would tilt proportional to the magnitude of the EDM. Therefore, to achieve the better EDM sensitivity, the better decay point identification is required, and then, the better muon beam control in the storage ring is required. More details of the new experiment will be found in [3]. In this paper, we discuss how do we guide and control the muon beam into the storage ring.

OUTLINE OF NEW INJECTION SCHEME

We plan to utilize a 3 T MRI-type solenoid magnet to store the muon beam of 300 MeV/ c . The muon cyclotron radius becomes 0.33 m. This number is an order of smaller or even several orders of smaller than commonly used storage rings in the world. Because conventional beam injection methods are not applicable in our case, we have been developing a

new spiral injection scheme instead, as displayed in Fig. 1. Outline of a basic concept, followed by the muon storage ring and requirements of the muon beam phase space parameters, will be discussed in the next sections.

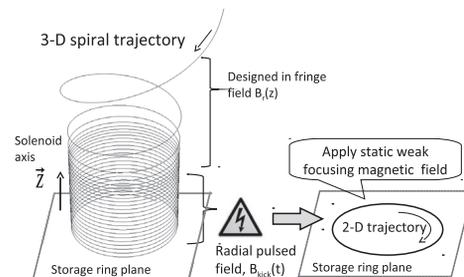


Figure 1: Outline of the three-dimensional injection scheme. The muon beam enters from obliquely upward through a solenoid fringe field. See more details in [4].

Basic Concept

As in Fig. 1, the muon beam enters from obliquely upward through a solenoid fringe field. The beam momentum is deflected by a radial component of the fringe field B_r as it reaches to the mid plane of the solenoid magnet. We proactively take advantage of the fringe field to control beam vertical motion. Then, a vertical pulsed magnetic kick B_{kick} will guide the beam inside the storage volume. A static weak-focusing field will maintain the beam in the storage region for several tens microseconds [3, 4]. In the sequence of injection, there is no need for the electric field to control the beam at all. This is one of the important features of this injection scheme to avoid any disturbance for the muon spin.

Compact Storage Ring

Figure 2 shows an image of solenoid type storage magnet of one-quarter cut view, with sample trajectories. Return iron yoke covers superconductive solenoid coils to avoid error field from the outside of the magnet. The beam from obliquely upward is injected through a channel in the return iron yoke. Kicker coils are also shown only partially. More details of the storage magnet and the vertical kicker can be found in [5] and [4], respectively.

Beam Phase Space Requirements

Figure 3 depict three-dimensional view of trajectories in the injection volume for two cases. For both cases, beam has the same emittance $\sigma_\epsilon = 0.1\pi$ mm-mrad for horizontal and vertical, but different in shape of the beam phase spaces.

* hiromi.iinuma.spin@vc.ibaraki.ac.jp

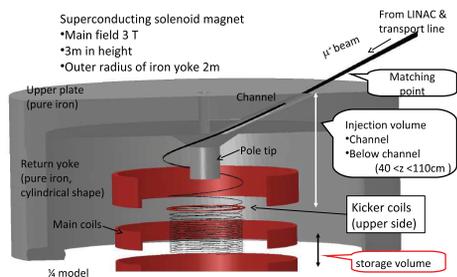


Figure 2: One-quarter cut view of the MRI-type solenoid magnet for the beam storage. See more details in [5].

It is clear that the right case has appropriate beam phase spaces, but the left one is not. Because of an axial symmetric shape in the solenoidal field, appropriate vertical-horizontal coupling (X - Y coupling in the beam coordinate) is required to control vertical divergence. Comparisons of beam phase spaces in the beam coordinate at the injection point are shown in Fig 4.

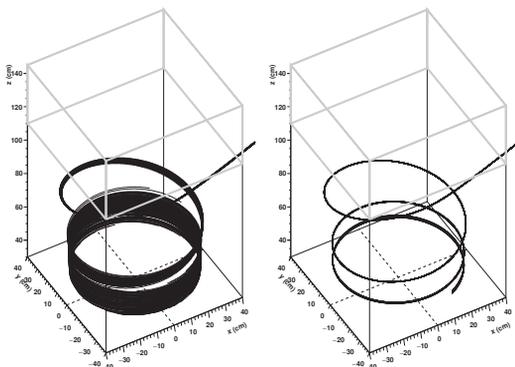


Figure 3: Beam tracking simulation. Left: simple gaussian shape of $\sigma_\epsilon = 0.1\pi$ mm-mrad. Right: The same emittance but applying an appropriate vertical-horizontal (X - Y) coupling.

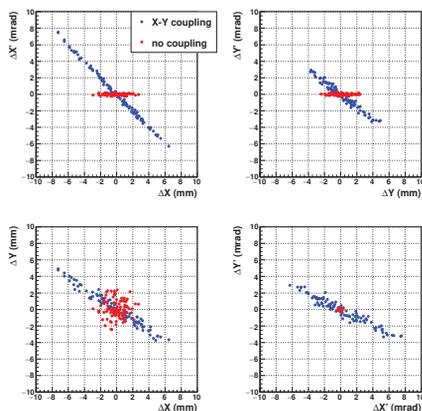


Figure 4: Comparisons of beam phase spaces in the beam coordinate at the injection point. Blue points have appropriate vertical-horizontal coupling (X - Y coupling), while red points do not.

The left side of Fig. 5 depicts radial component of the fringe field in the injection volume. A closer look of the three-dimensional beam with appropriate X - Y coupling is also shown in the right. Open blue circles along the beam indicate points 1 ~ 9 from the bottom. Black points in Fig. 6 depict vertical beam phase slices at the point 1 to 9 referred in Fig. 5, and point 0 (Injection point outside of the magnet). The vertical beam phase space minimizes at the height at 70 ~ 60 cm as a focal point with given B_r . Below this focal point, the vertical beam phase space diverges as it reaches to the storage volume region. In the worst case, the vertical beam phase space gets bigger than the vertical kicker acceptance (blue region in the right bottom plot in Fig. 6). Vertical beam phase space matching with the kicker acceptance is a current major working item. If we invite another vertical focus magnetic field below the focal point, say at $z \sim 60$ cm, we could inhibit vertical divergence of the beam (red points in Fig. 6). A design of additional quadrupole magnet in the region of $60 \leq z \leq 70$ cm region is under consideration.

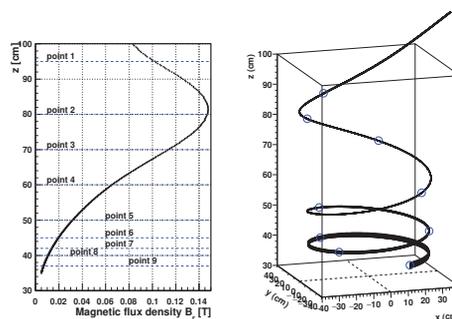


Figure 5: Left: Radial component of fringe field in the injection volume. Right: Closer look of three-dimensional beam with open blue circles, which indicate points 1 ~ 9.

ELECTRON ANALOG TEST EXPERIMENT

Test bench works have been started in order to realize three-dimensional injection scheme by use of electron beam [6]. The goal of this test experiment is to store the pulsed beam for the order of milliseconds within a storage volume.

Table 1 compares the parameters of the original experiment and this electron analog test experiment.

Although the storage orbit is 1/3 scale of the original one, weak focusing field by auxiliary coils and a vertical kicker system are available. The biggest point of this test experiment is to visualize three-dimensional trajectory. The storage chamber was filled with nitrogen gas, which allows us to detect the electron beam as a fluorescent light due to the de-excitation of the nitrogen gas.

Figure 7 introduces pictures of this test beam line. An electron beam from an electron gun goes through in a straight beam pipe for 80 cm. A vertical dipole magnet bends the beam at 40 degrees towards an injection hole in the storage

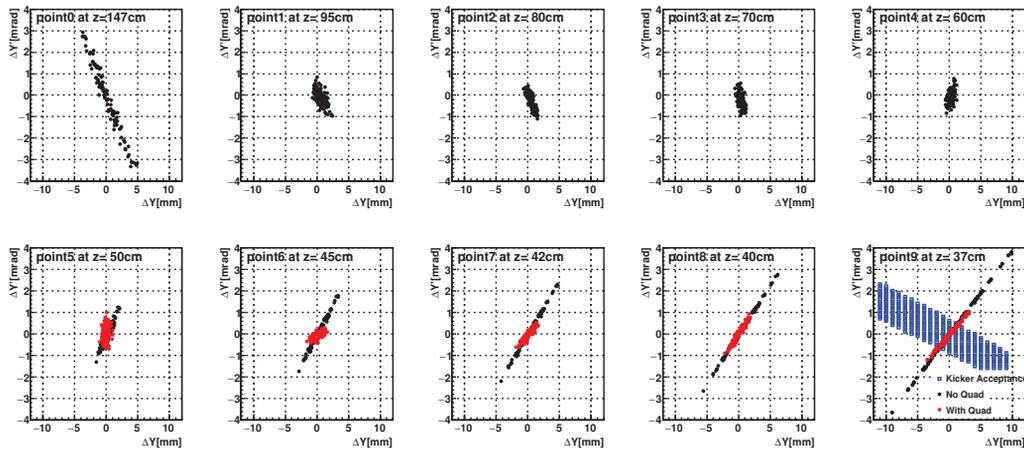


Figure 6: Black points depict vertical beam phase slices at the point 1 to 9 referred in Fig. 5, and point 0. The vertical beam phase space minimizes at the height at 70 ~ 60 cm as a focal point. Red points depict a case if apply additional quadrupole magnet at $z \sim 60$ cm to minimize vertical divergence, in order to meet the vertical kicker acceptance (blue region in the right bottom plot).

Table 1: Comparison of Basic Parameters of the g -2/EDM Experiment at J-PARC and This Test Experiment

items	g -2/EDM (J-PARC)	Electron analog test experiment
Storage magnetic field	3.00 T	80 ~ 100 Gauss
Beam particle	μ^+ (pulse)	electron (DC or pulse)
Momentum	300[MeV/c]	300 ~ 330[keV/c]
cyclotron period	7.4[ns]	~ 5[ns]
Storage orbit radius	0.33[m]	0.12[m]

chamber (see picture B in Figure 7), inside of a solenoid magnet.

Figure 8 is one of example pictures in the storage chamber with the DC electron beam. The vertical beam size gets bigger as the beam approaches to the mid plane of the solenoidal field, because the beam is not properly X - Y coupled yet. We are going to install rotating quadrupole magnet(s) very soon, and will continue commissioning to obtain the better matching parameter.

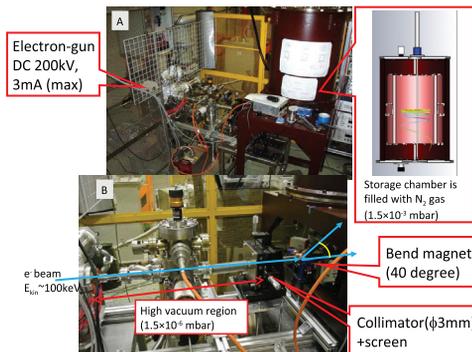


Figure 7: Test beam line sited at the LINAC building in the KEK Tsukuba campus [6].

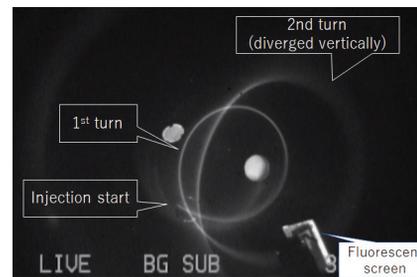


Figure 8: Example picture of visualized three-dimensional trajectory. Fluorescence emission of the nitrogen molecules is induced by the electron beam.

CONCLUSION

A new concept of the beam injection scheme, which aims to inject a beam into the sub-meter size of the compact ring, and status of the bench works were introduced. Our plan is to utilize a 3 T MRI type solenoid magnet as a storage magnet. We discussed a need for the appropriate X - Y coupling for the beam phase space to meet the axial symmetric fringe field. We also introduce current working item: inviting additional vertical focus field to minimize vertical divergence below the focal point. A three-dimensional spiral trajectory as a visible light from the test bench work was also introduced. Further work to achieve the best X - Y coupling parameter will be completed in coming few months.

ACKNOWLEDGMENT

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