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RESULTS FROM VALIDATION EXPERIMENT FOR THREE-DIMENSIONAL SPIRAL BEAM INJECTION SCHEME*

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Abstract

A proof of principle experiment of "Three-dimensional spiral beam injection scheme" at J-PARC muon g-2/EDM experiment has been carried out. This injection scheme requires a strongly X-Y coupled beam to meet magnetic field distribution through solenoid magnet fringe field. In this paper, we introduce outline of experimental setup, results of X-Y coupling adjustment with DC electron beam of 80 keV. We also introduce a vertical kicker and a weak focusing field to maintain the *chopped* beam inside the fiducial volume, as well as preliminary results of beam storage.

MOTIVATION

A proof of principle experiment had been carried out for three-dimensional injection scheme prior to J-PARC muon g-2/EDM experiment [1] which aims a different approach to those of previous muon g-2 experiments. This new experiment will utilize a low-momentum (γ = 3) with small emittance muon beam which can be maintained in the storage ring by use of a weak focusing magnet only till the end of its lifetime ($\gamma\tau$ = 6.6 μs).

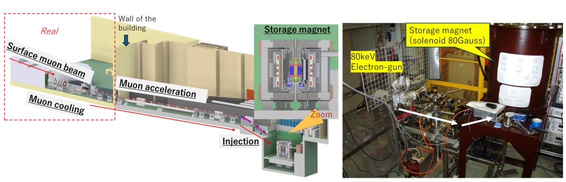

Figure 1: Left:Image of J-PARC muon b-2/EDM beam line. Right: A photo of test beam line.

An image of beam line of J-PARC g-2/EDM experiment in the left of Fig. 1. An unit of 3 T MRI-type solenoid magnet located at the end of the beam line for storage a muon beam [1]. A diameter of the orbital cyclotron motion becomes only 0.66 m, which is a factor of 20 smaller than that of the former experiments using a so-called magic momentum γ = 29.3. Because a conventional beam injection method in our case is not applicable, we have developed a brand-new injection scheme; namely three-dimensional spiral injection scheme.

Beam phase space of spiral motion in the solenoidal magnetic field tends to spread along the solenoidal axis direction because there is no force to control it. To avoid vertical beam spread, phase space should be well adjusted to have an appropriate correlation between solenoidal and radial axes (so-called X-Y coupling) with given solenoidal fringe field at an injection point. Figure 2 depicts comparison of beam tracking with/without X-Y coupled phase spaces

To demonstrate feasibility of X-Y coupling design and its operation, we set goals for the test beam line as listed below;

- design appropriate X-Y coupling [2–4],
- measure and control X-Y beam phase space at the transport line,
- Verify that the actual beam phase space corresponds to the beam dynamics calculations.

In this paper, we discuss about the 2nd and 3rd items mainly.

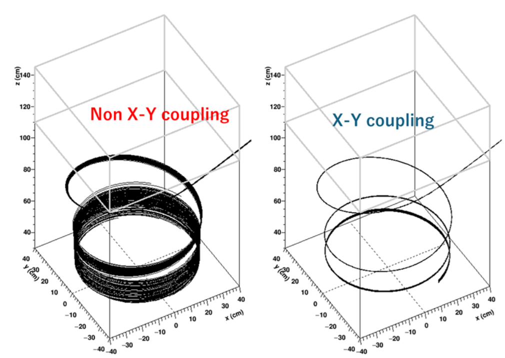

Figure 2: Left: Three-dimensional beam tracking without appropriate X-Y coupling. Right: The same but applied appropriate X-Y coupling with regards to given magnetic field [2].

EXPERIMENTAL SETUP

A picture of test beam line to demonstrate a new concept of beam injection scheme is shown in the right photo of Fig. 1. Some major parameters are listed in Table 1 as well as parameters for actual experiment.

Instead of muon beam, we utilize an electron beam of 80 keV(β=0.5) from an electron-gun. A flux of storage magnetic field is only 80 Gauss, and radius of stored beam orbit is only 11 cm. This may be smallest ring in the world of relativistic energy beam injected from outside.

Figure 3 depicts outline of the beam line from the electron-gun through the storage magnet. The 80 keV DC electron

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Table 1: Comparison of Basic Parameters

Items	J-PARC g-2/EDM (design)	this exp.
magnetic field	3.0 T (<0.1ppm)	80 Gauss
Beam particle	μ^+	e^-
momentum	300 MeV/c	300 keV/c
cyclotron period	7.4 ns	5 ns
ring radius	0.33 m	0.11 m
Weak index:n	5×10^{-4}	$(1 \sim 6) \times 10^{-2}$
Kicker current	1.2kA/coil	45A/coil
Kicker duration	120 ns	100 ns

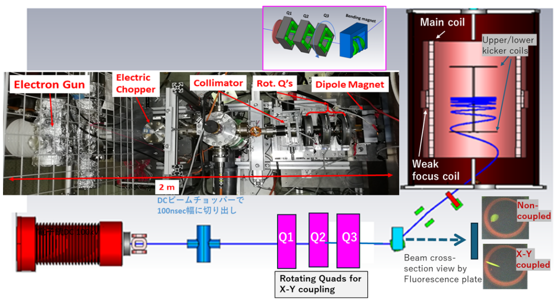

Figure 3: Outline of the test beam line.

beam($\sim 60\,\mu$A) from the electron gun passes through a transport line with a total length of about 2 m, and is divided by a bend magnet into an injection line and a beam diagnostic line. The electron beam that has traveled through the injection beamline is injected into a solenoid magnet from below at an angle of 44 degrees. The solenoid magnet which is surrounded by iron yoke is made up of a main solenoid field and a weak focusing field. Due to appropriate quadrupole magnetic fields for both vertically and radially, the beam can stay inside the fiducial volume with following vertical and horizontal betatron motions. The storage magnet also contains a vertical kicker device to change the vertical beam motion to a horizontal direction. This kicker device and the weak focusing magnetic field will be discussed later section.

X-Y COUPLED BEAM OPERATION

At the end of the straight section in Fig. 3, there is an copper plate to detect cross-section view of beam. Example pictures named "Non X-Y coupled" and "X-Y coupled" beams. Three rotating quadruple magnets are utilized to try several types of X-Y coupling.

Figure 4 depicts beam cross-section views with twenty different quadruple settings to estimate beam space parameters. In general, X-Y coupled beam is expressed in ten parameters (ϵ_x, ϵ_y, α_x,α_y,β_x,β_y, and r_1,r_2,r_3 and r_4)[1], and we estimated them from the measured data. In general, eight parameters except for emittance should be controlled with at least eight independent tuning knobs. However, we have only six tuning knob (three rotating angles, three K-values), be-

[1] we treat transverse phase space only in this paper.

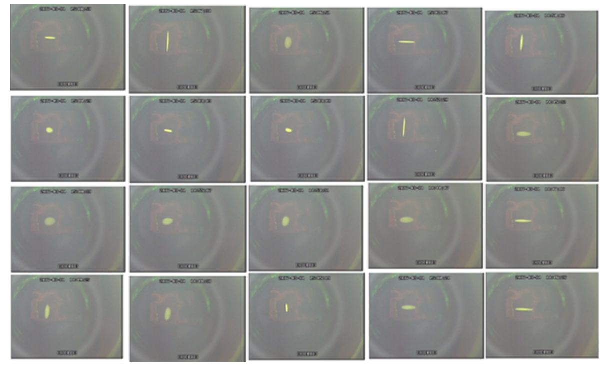
Figure 4: Twenty views of beam cross-section at the end of the straight line , by changing settings of three rotating quadrupole magnets as in Fig. 3.

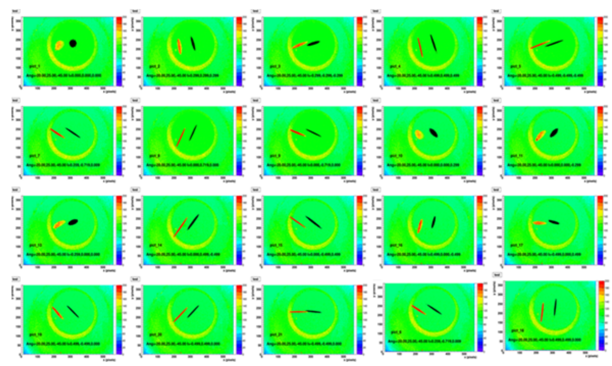
Figure 5: Comparisons of simulations and measurements as in Fig. 4 to confirm we control the beam line well.

cause of space limitation. Therefore, our system takes steps to prioritize and adjust the X-Y and y-y' correlations to be ideal. Figure 5 depicts comparisons of twenty cross-section views of real and simulated beam shapes. The brightness of the color images in Fig. 4 are converted to one dimension, and the ADC values of each pixel of the camera are converted to two-dimensional histograms in Fig. 5. There are compared with calculated X-Y distributions in black dots. Note that the design in actual experiment in J-PARC is made redundant using seven rotating quadrupole magnets [2] to adjust six phase-space correlations (x-x', y-y', x-y, x-y' and y-x' in the beam coordinate).

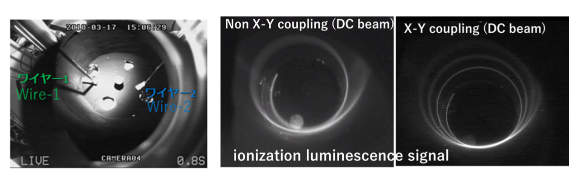

Figure 6: Internal views of storage chamber as well as visualized electron beams.

Figure 6 depicts internal views of storage chamber inside the storage magnet. As in the left plot, there are two vertical wire (or scintillating fibers) probes to detect injected DC (or pulsed) beam inside of the chamber. The two 3-dimensional

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beam trajectory images on the right visualize the electron beam ionizing nitrogen gas which is then used to semi-online confirm the X-Y coupling settings given in the transport line. There are clear difference with/without X-Y coupling as introduced in Fig. 3.

BEAM STORAGE

To maintain injected beam inside the storage magnet, we had modified the test beam line as:

- beam kicker device is installed [5, 6],
- DC beam is chopped out to 100 nsec [7],
- scintillating fiber probe is installed [8].

More details will be found in reference articles.

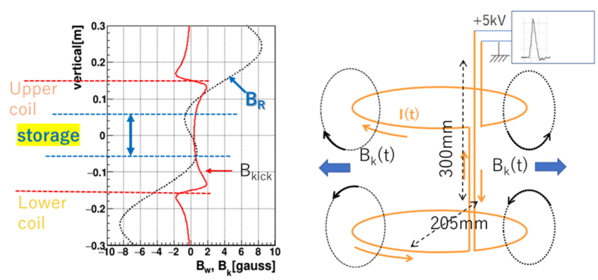

Figure 7: kicker system (right side) and radial field distribution along the solenoidal axis at radial point of 11 cm in red solid line.

Figure 7 depicts kicker system (right side) and radial field distribution along the solenoidal axis at radial point of 11 cm in red solid line [6]. Blue dotted line is radial field created by a main coil and weak focusing coil. Vertical (=solenoid axis) storage area has quadratic magnetic field. Inside that volume, the beam is follow vertical and horizontal betatron oscillations; namely VBO and HBO. Kicker system is a series-connected pair of copper coil. By passing currents in opposite directions through the upper and lower coils, a radial pulsed magnetic field is generated to bend the beam direction into horizontal motion only at the mid plane (z=0 in the figure).

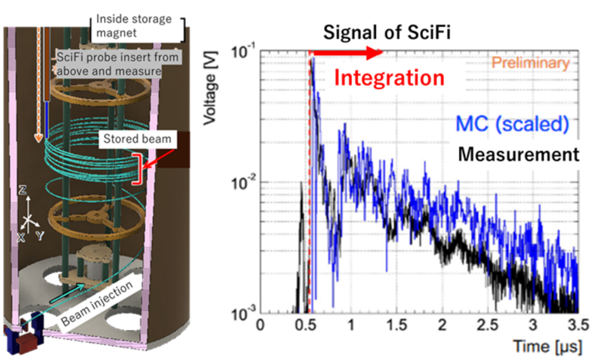

Figure 8: Left: Experimental setup for pulsed beam operation. Right: Signal of stored beam by use of SciFi.

Left plot of Fig. 8 depicts stored beam image with kicker coil and scintillating fiber (SciFi) probe. Measured beam is shown as a function of time as well as simulation (blue) in the right plot. It is clear that stored beam is detected more than few micro-seconds in the storage volume by SciFi probe destructively. This is well longer than a period of pulsed (100 nsec) beam. There are two major time structures are found; decay and oscillations. Decay occurs because electrons are detected in the SciFi and disappear there.

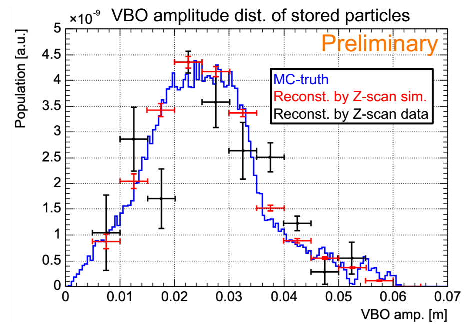

Figure 9: Reconstruucted VBO distribution by use of a set of vertical scan data as in Fig. 8. Blue solid line and black points are simulations as explaind in the main text.

Black crosses in Fig. 9 depicts preliminary results of the VBO distribution obtained from a set of z-scan as in Fig. 8 data. Vertical uncertainty comes from statistics and horizontal uncertainty is from SciFi positions. Blue histogram is simulation and red dots are reconstruction predictions using simulation data and detector conditions. Dedicated analysis for the final results is underway and it will be published very soon.

SUMMARY AND NEXT

In this paper, a proof of principle experiment for three-dimensional spiral injection scheme is introduced. Firstly, we introduce appropriate X-Y coupling is applied via transport line with three rotating quadruples following experimental setup. Visualized three-dimensional beam views are introduced with/without applying appropriate X-Y coupling by use of three rotating quadrupole magnets. We have introduced weak focusing potential as well as VBO. The kicker system is also introduced to bend the beam into the horizontal motion. Though experimental parameters shown in 1 different from the actual experiment, dynamics of three-dimensional injection scheme is same. The principles of each piece of equipment included in the experimental setup are the same as in actual experiments.

Final results will be publish soon and we will feedback there knowledge on the design works of the actual experiment supposed to start in 2030.

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