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DEVELOPMENTS OF A PULSE KICKER SYSTEM FOR THE THREE-DIMENSIONAL SPIRAL BEAM INJECTION OF THE J-PARC MUON g-2/EDM EXPERIMENT*

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Abstract

The J-PARC muon $g-2$/EDM experiment aims to perform ultra-precise measurements of anomalous magnetic moments ($g-2$) and electric dipole moments (EDM) from the spin precession of muons in a precise magnetic field, and to explore new physics beyond the Standard Model. On experimental requirements, the beam must be stored in a compact storage orbit with a diameter of 66 cm, which is about 1/20th smaller than that of the previous experiment. To be realized, we adopt an unprecedented injection technique called three-dimensional spiral injection scheme. In this scheme, the beam is injected from upward of the solenoidal storage magnet. The vertical beam motion along the solenoid axis is controlled by a pulse kicker of a few 100 ns time duration. Once the beam is guided into the center fiducial storage volume, the muon beam is stored by the weak focusing magnetic field. Therefore, stable and accurate control of the pulse kicker is one of the major technical challenges to realize ultra-precise measurement of the muon spin precession.

In this presentation, we discuss a performance of the prototype pulse kicker device and future plan for installation of it to our test bench with an electron beam.

INTRODUCTION

The J-PARC muon $g-2$/EDM experiment [1] is planning at the J-PARC muon beamline. The goal of this experiment is to search for new physics beyond the Standard Model of elementary particles [2] by making ultra-precise measurements of the anomalous magnetic moments ($g-2$) and electric dipole moments (EDM) from the spin precession of muons in a precise magnetic field. On experimental requirements, the beam must be injected into a storage orbit with a diameter of 66 cm, about 1/20th of the previous experiment (BNL-E821) [3]. Therefore, it is technically difficult to kick into a storage orbit of 66 cm in diameter within one cyclotron period (7 ns) by the same injection scheme as the previous experiment. In order to solve this technical problem, we have adopted a new injection technique named Three-Dimensional Spiral Injection Scheme [4]. This injection scheme is unprecedented, and we are developing the technology for the injection scheme and conducting demonstration experiments.

The image of the beam injected by the three-dimensional spiral injection scheme is shown in Fig. 1. In this injection scheme, the beam is first injected from upward of the storage solenoid magnet and moves in a spiral motion using the fringe field of the solenoid magnet. Next, by creating a radial magnetic field there, the beam is given a vertical kick, and we can guides the axial motion of the solenoid and keeps the beam in the storage region at the center of the solenoid magnet. Finally, the beam is stored in a circular storage orbit on an almost two-dimensional plane by a weak focusing magnetic field. For the success of this injection, the generation of the kicker field is essential, and the accurate kick is directly related to the high injection efficiency of the muon beam.

In this paper, we report the results of the stand-alone performance evaluation of a prototype pulse magnetic field kicker device, which will be installed in a test bench for the demonstration of the three-dimensional spiral injection scheme using an electron beam at KEK Tsukuba.

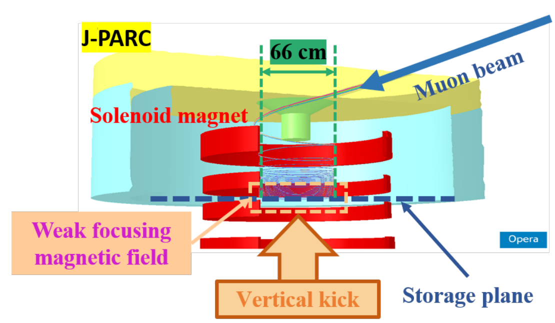

Figure 1: Image of the beam injected by the three-dimensional spiral injection scheme.

PULSE MAGNETIC FIELD KICKER DEVICE

The kicker magnetic field is created by a pulse magnetic field kicker device. A photograph of a prototype the pulse magnetic field kicker device for our test bench with the electron beam, and the schematic diagram of the coil arrangement and the radial magnetic field generation of this kicker

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device is shown in Fig. 2. This kicker device has one-turn coils symmetrically above and below the storage plane, and the radial magnetic field is created by applying a half-sine pulse current in the opposite direction to each of the coils.

The shape of the magnetic field distribution created by this prototype kicker coil, measured with a pickup coil and calculated from the Biot-Savart law, is shown in Fig. 3. This solenoid axisymmetric radial magnetic field Br gives a vertical kick according to Fleming's left-hand rule and reduces the component of particle momentum in the direction of the solenoid axis.

Thanks to the compact orbit, we can install a kicker system that can give kicks over multiple cyclotron cycles, so that kicks do not have to be completed within one cyclotron cycle as in the previous experiment (BNL-E821). However, in order to achieve a kick field that matches the cyclotron orbit, the inductance of the kicker coil becomes larger and the voltage of the kicker power supply becomes higher, so realistic parameter adjustments must be carefully made.

In addition, the kick can be given without disturbing the orbit center because the magnetic field Bz in the solenoid axial direction are distributed at the storage plane to cancel each other and the kicker magnetic field is axisymmetric.

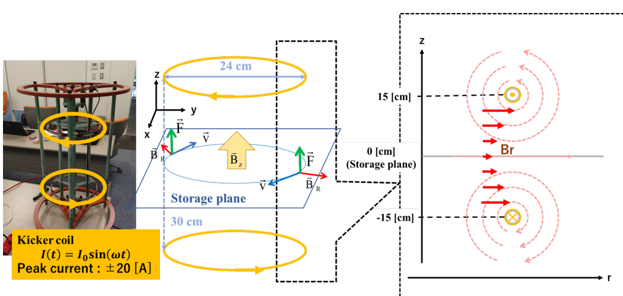

Figure 2: Prototype pulse magnetic field kicker device for our test bench with the electron beam, and the schematic diagram of the coil arrangement and the radial magnetic field generation of this kicker device.

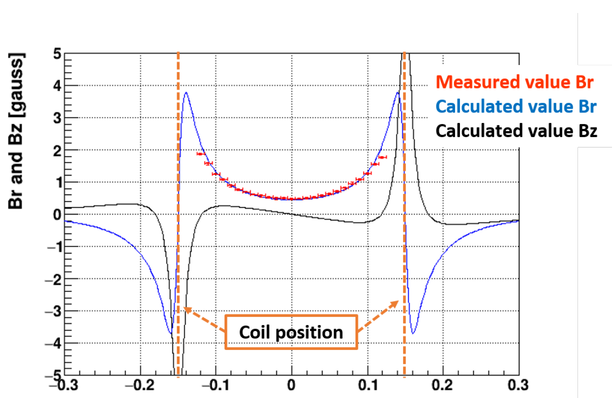

Figure 3: Calculation results of the magnetic field distribution created by the kicker coil and the radial magnetic field distribution measured by the pickup coil.

THE STAND-ALONE PERFORMANCE OF THE PULSE KICKER DEVICE

Before installing this kicker device on our test bench, we conducted a stand-alone evaluation to check the stand-alone performance and response of the pulse magnetic field kicker device.

The main specifications of the pulse power supply for the kicker for the test bench are shown in Table 1.

Table 1: Main Specifications of the Pulse Power Supply for the Kicker for the Test Bench

Item	Specification
Peak current	40 A (20 A+20 A)
Current rise time	25 ns
Current fall time	50 ns
Load inductance	1.5 μH
Supply voltage	5 kV
Repetition	50 Hz

We conducted the performance evaluations of the kicker coil and the pulse power supply in several items. In this paper, we report on the stability of kicker timing, and the consideration of pulse current waveform.

Experimental Setup for Stand-alone Performance Evaluation Measurement

The experimental setup is shown in Fig. 4. The function generator creates a trigger signal, and the pulse power supply for kicker connected to the high-voltage power supply sends a pulse current to the kicker coil in synchronization with the signal. This current signal is acquired by a current transformer that supports 1V/10A.

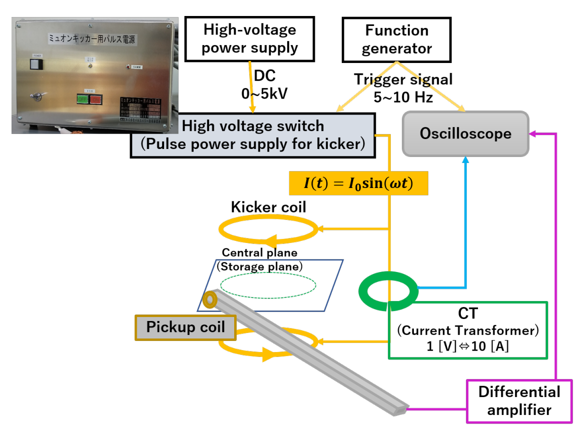

Figure 4: Experimental setup for stand-alone performance evaluation measurement.

Stability of Kicker Timing

As the first item, we checked the time stability of the kicker timing. If the kicker power supply does not coincide with the trigger signal stably, it will be difficult to apply

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the kicker magnetic field at the correct timing. An example of the kicker current signal as seen on the oscilloscope is shown in Fig. 5. To check the time difference between the rise time of the trigger signal and the kicker current signal, we measured the average value and standard deviation of the time difference of each signal using an oscilloscope while changing the supply voltage by 1 kV (from 1 kV to 4 kV). At 1 kV, the kicker current was 65 A, and as the supply voltage increased by 1 kV, the kicker current increased by around 55 A. The definition of rise time was the time difference between 50 % of each signal, and the number of signal samples used to obtain the average value and the standard deviation was 1 000 waveforms per measurement point.

The measurement results are shown in Fig. 6. The left plot (a) is the average of the time difference, and the right plot (b) is the standard deviation of the time difference.

From the results on the left (a), we can see that as the power supply voltage is increased, the timing of the current signal rising becomes slower around 4 ns/175 A in total. This shows that the rise time of the kicker current signal has a current dependency of 4 ns/175 A, so the trigger timing of the kicker must be determined according to the current waveform, and the correlation between the current and the appropriate trigger timing must be properly suppressed.

The results on the right (b) show that the standard deviation is around 0.3 ns regardless of the value of the voltage. It is small enough compared to the cyclotron period of 5 ns and the kick time width of 70 ns at the test bench.

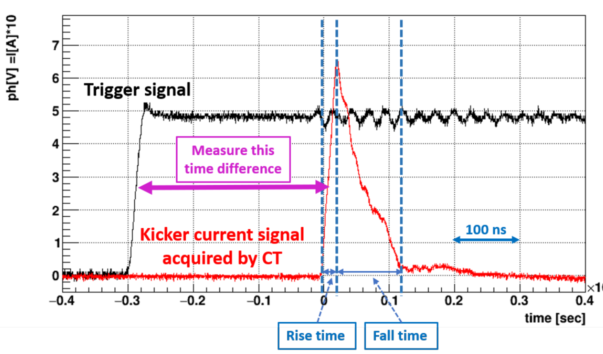

Figure 5: Kicker current signal as seen on the oscilloscope (Supply voltage : 1 kV).

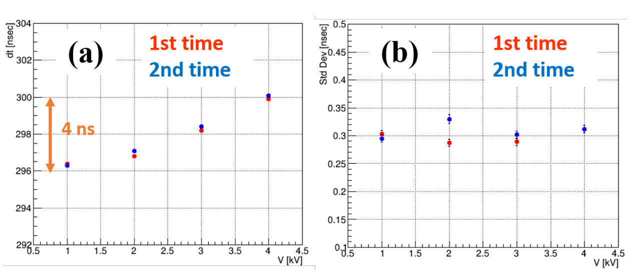

Figure 6: Measurement results average (a) and standard deviation (b) of the time difference between the trigger signal and the rise of the kicker current signal.

Consideration of Pulse Current Waveform

As the second item, we will focus on the waveform of the pulse current (kicker current) acquired from the Current Transformer at the same time as we measured the average and standard deviation of the time difference. The rise and fall times of the current signal, which can be confirmed from this waveform, were compared with the specifications of the pulse power supply for the kicker for the test bench (Table 1).

According to the Fig. 5, The rise time is 20 ns. This value meets the specification. However, the fall time is 100 ns. Although, it doesn't meet the specification, but the power supply alone meets the specification. Cable placement such as inductance or reflection between the kicker coil and the power supply is a possible cause. Understanding the reason will be the future problem.

In addition, I was using an ideal current with a half-sine waveform in the simulation, but the actual waveform didn't have a half-sine waveform. In the future, we will replace to the real current waveform from the simple half-sine waveform to improve accuracy of the simulation. Also, we will check the peak current dependence of the waveform.

SUMMARY AND FUTURE PLANS

In the J-PARC muon g-2/EDM experiment, muon beams are injected and stored by a new injection technique named Three-Dimensional Spiral Injection Scheme. As a part of the process of the injection scheme, a pulse magnetic field kicker device is used to guide the axial motion of the solenoid and to keep the beam in the storage region at the center of the solenoid magnet. We are currently conducting a demonstration experiment of three-dimensional spiral injection scheme at the test bench with electron beam, and before installing the pulse magnetic field kicker device for the test bench there, we conducted a stand-alone performance evaluation.

It was found that the kicker timing jitter was small enough compared to the cyclotron period and the kick time width at the test bench. But it was also found that the trigger timing needed to be adjusted to account for the dependence of the supply voltage. The rise time of the pulse current met the specification, but the fall time took longer than the specification.

In the future, we need to deepen our study to install the kicker device on the test bench with electron beam and run it as a system. Specifically, we need to understand the resistance caused by cable placement that may be the cause of delay in the fall time, replace to the real current waveform from the simple half-sine waveform to improve accuracy of the simulation, and determine the kicker timing after installation.

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