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DEVELOPMENT OF PULSED BEAM SYSTEM FOR THE THREE DIMENSIONAL SPIRAL INJECTION SCHEME IN THE J-PARC MUON g-2/EDM EXPERIMENT*

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Abstract

The J-PARC muon g-2/EDM experiment aims to measure the anomalous magnetic moment (g-2) and electric dipole moment (EDM) of the muon with higher precision than the previous BNL E821 experiment. A brand-new three-dimensional spiral injection scheme is employed to inject and store muon beam into a 66 cm diameter of storage magnet. Feasibility studies are ongoing by use of 80 keV electron beam at KEK test bench, to develop skills on control transverse beam motion; so-called X-Y coupling, with DC beam. As a next step, towards store the beam by use of a kicker system, a pulsed beam should be generated from the DC beam with an intended time structure to meet a pulse kicker's duration time, without changing transverse phase space characteristics. In this presentation, the development of a beam chopper device and the evaluation of pulse beam profile are discussed.

INTRODUCTION

The anomalous magnetic moment of the muon (g-2) is a physical quantity that directly represents the magnitude of the quantum corrections to the muon. Previous measurements at Brookhaven National Laboratory (BNL) [1] and Fermi National Accelerator Laboratory (Fermilab) [2] have shown that this quantity deviates from the value predicted by the Standard Model of particle physics [3] by 4.2σ. At Japan Proton Accelerator Research Complex (J-PARC) , an experiment using a different method from the previous experiment, the J-PARC E34 experiment [4], is under preparation, aiming to measure muon g-2 with a high precision of 0.5 ppm and Electric Dipole Moment (EDM) with the world's highest sensitivity of 10^{-21} e·cm. In the E34 experiment, the three-dimensional spiral injection scheme [5] will be used to inject and store the beam into the 66 cm diameter storage superconducting magnet with magnetic field strength of 3 T. In this method, the beam is injected at an injection angle of about 440 mrad, and then the injection angle is reduced to about 40 mrad during the first three turns by the fringe magnetic field of the solenoid magnet, which is the storage magnet. Where the injection angle is the angle between the horizontal plane and the direction of the beam. Then, the kicker installed inside the storage magnet generates the pulsed magnetic field to further reduce the injection angle, and finally the injection angle is reduced to a few mrad at the storage plane. Finally, the beam is applied weak focusing by the radial magnetic field adjusted to satisfy $B_r = -n\frac{B_0}{r_0}z$ in the range of $|z| = 5$ cm around the storage plane, and the beam is stored by the betatron oscillation on the plane perpendicular to the beam direction around the storage plane (Fig. 1). Where $B_0 = 3$ T is magnetic field strength of the storage magnet, $r_0 = 33.3$ cm is cyclotron radius of the beam, n is the field index and z is the position in the vertical direction.

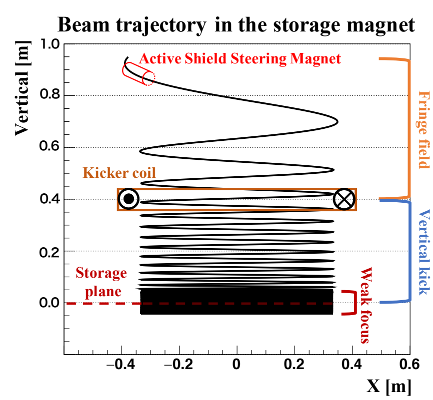

Figure 1: Beam trajectory inside the storage magnet. After injection, the injection angle is reduced to 40 mrad by the fringe field of the solenoid magnet until vertical>0.4 m. After vertical≤0.4 m, the beam is kicked in the vertical direction by the pulsed magnetic field generated by the kicker, and the injection angle is reduced to a few mrad at the storage plane (vertical=0 m). Finally, the beam is applied weak focusing by the inclined magnetic field around the storage plane and is stored by betatron oscillation in the plane perpendicular to the beam direction.

The advantage of this method is that the beam is stored without using any electric field, so there is no need to make corrections due to the electric field, as was done in the previous experiments at BNL and Fermilab [6], and allows us to measure the muon g-2 and EDM in a different way than before.

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For this strategy to successfully work, it is necessary to control the injection angle and the trajectory of the beam in the injection region (vertical>0.4 m). The injection angle of the injection orbit is controlled by the spatial distribution of the fringe field in the injection region of the storage superconducting magnet. The Active Shield Steering Magnet (ASSM) will be installed to fine-tune the injection angle in the injection region and to provide feedback control to achieve the beam injection angle as designed. Precise monitoring of the injection trajectory is essential for this purpose, and I am working on an injection demonstration experiment at the test bench as part of the basic study of this part.

The three-dimensional spiral injection scheme is the first attempt in the world. Therefore, we are constructing a test bench using electrons instead of muons at KEK and conducting experiments to establish the injection scheme. In the previous studies, we have obtained some results of controlling the phase space of the beam (so-called XY coupling) using DC beams [7]. By applying XY coupling to the beam, we achieved a good spiral injection orbit in the storage magnet. The next step is the demonstration experiment of storing the pulsed beam using the kicker. For this purpose, we constructed the chopper system to produce the pulsed beam with the intended time structure from the DC beam.

PULSED BEAM GENERATION: CHOPPER SYSTEM

The chopper system consists of a pulse power supply [8] and a pair of electrodes facing each other (Fig. 2). A conceptual diagram of the pulsed beam generation is shown in Fig. 3. The pulsed beam is cut out from the DC beam by applying a pulsed electric field to a pair of electrode plates, as shown in Fig. 3(a). The concrete generation method is as follows: when ±H.V. is applied to both electrodes, respectively, the beam is deflected by the electric field formed between the electrodes and is blocked by the slit. On the other hand, when the voltage applied to both electrodes is 0 V, the beam is not deflected and passes through the slit (3 mmϕ). The pulse width and repetition frequency of the pulsed beam generated by the chopper system are determined by the time structure of the pulse voltage applied to the electrodes. The time structure of the pulse voltage output from the pulse power supply can be controlled by an externally input gate signal. Therefore, by adjusting the externally input gate signal, it is possible to generate the pulsed beam as intended. The performance range of the pulse power supply determines the time structure of the pulsed beam. More concretely, This chopper system can generate pulsed beams with pulse widths from 60 ns to DC and repetition frequency from single shot to <20 kHz. The specifications of the pulse power supply are shown in Table 1.

Checking the Injection Trajectory with the Pulsed Beam

At the test bench, we have two beam lines. One is an injection line to inject the beam into the storage magnet and the other is a straight line for beam diagnostics. We can fill the nitrogen gas in the storage magnet for beam trajectory visualization and nitrogen gas emits blue-light wavelength range of 390 nm $< \lambda <$ 470 nm. so we can capture the trajectory by a CCD camera mounted on the top of the storage magnet. The installed wire scanner can also be used to measure the vertical beam distribution inside the storage magnet. The DC beam and the pulsed beam with a pulse width of 100 µs generated by the chopper were injected into the storage magnet under the same conditions. Photos of the beam trajectory taken by a CCD camera is shown in Fig. 4, and the result of wire scan in the vertical

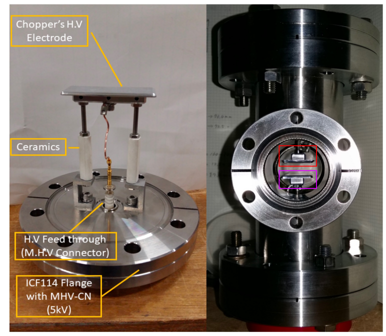

Figure 2: The photo on the left shows the electrode, which is 25 mm × 35 mm in size. In the photo on the right, the upper electrode is surrounded by the red line, and the lower electrode is surrounded by the purple line. The distance between the electrodes is 10 mm, and the beam passes between them in the vertical direction on the paper. [7]

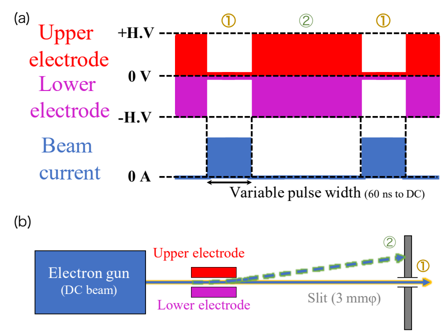

Figure 3: Schematic of pulsed beam generation by chopper system. If the voltage applied to the top and bottom electrodes is 0 V, the beam passes through the slit without being deflected (①). If a voltage of ±H.V is applied to the top and bottom electrodes, the beam is deflected by the electric field between the electrodes and does not pass through the slit (②).

Table 1: The specifications of the pulse power supply [8]

Output voltage (2 ch)	0 to +905 V \pm5 V (ch.1) 0 to -950 V \pm5 V (ch.2)
Pulse width(FWHM)	<50 ns to DC
Repetition frequency	Single shot to >20 kHz

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direction is shown in Fig. 5. This result confirms that there is no significant difference the orbits between the DC beam and the pulsed beam. However, we know from simulation studies that the acceptance of the kicker to the pulse width is about 28 ns, but the amount of charge is too small to measure the beam trajectory by wire scan or to take photo by CCD camera. Therefore, it is necessary to establish another monitoring method.

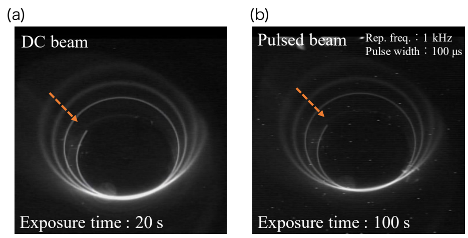

Figure 4: Beam trajectory inside the storage magnet of the (a)DC beam and (b)pulsed beam with 100 µs pulse width. The wire scan is performed in the direction of the orange arrow to measure the vertical beam distribution.

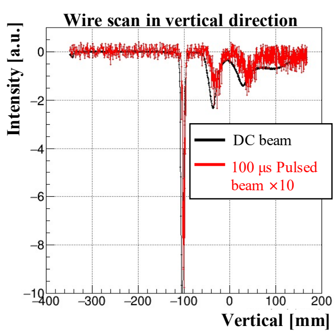

Figure 5: Results of wire scan. Black is the result of DC beam and red is the pulsed beam. The pulsed beam result is scaled by a factor of 10 to make the charge equal to the DC beam.

Checking the Pulse Width of the Pulsed Beam

At the end of the straight line, a scintillation fiber was inserted from the direction perpendicular to the beam as shown in Fig. 6, and we can measure the pulse width of the generated pulsed beam by observing the de-excitation light of nitrogen gas that leaks from the storage magnet excited by the beam. To confirm that the pulsed beam was generated as intended, the pulse width (FWHM) of the signal output from the PMT was measured by varying the pulse width (FWHM) of the gate signal input to the pulse power supply from 5 ms to 60 ns (limit of the pulse power supply). Some signals of PMT measured by an oscilloscope are shown in Fig. 7, and result of measurement is shown in Fig. 8. From the measurement results, it was confirmed that the pulsed beam was generated with an accuracy of about 3% for the set pulse width.

This measurement method provided information about the pulse width of the pulsed beam. However, it does not provide information on the position of the beam and the beam intensity. So, we are working on a new method to quantitatively evaluate the position and time structure of the pulsed beam.

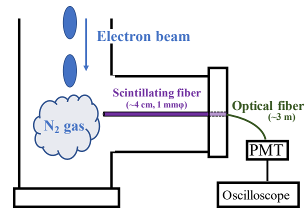

Figure 6: Measurement setup at the end of the straight line. The light from the scintillation fiber is transported by the optical fiber to the PMT and converted into an electrical signal.

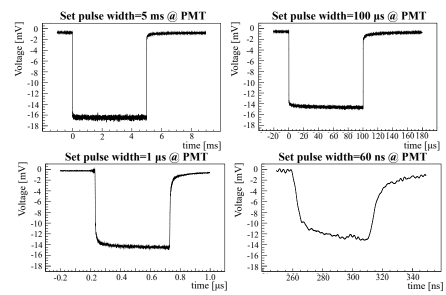

Figure 7: Some examples of PMT signals. Acquired as an average of 10,000 shots of pulsed beam. The magnitude of the signal height is not evaluated, only the time structure is evaluated.

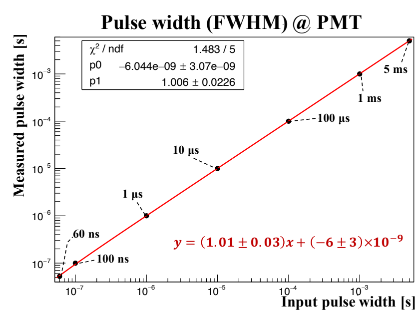

Figure 8: Measurement result of pulse width (FWHM) of PMT signal. From this result, we confirmed that the pulsed beam was generated with an accuracy of about 3% for the set pulse width.

CONCLUSION

We constructed a chopper system to generate the pulsed beam and confirmed that we can generate the pulsed beam with the intended pulse width. In the future, we will install the kicker and conduct a storage demonstration experiment and research and development of a method to monitor the pulsed beam.

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