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STRIPLINE-BASED NON-DESTRUCTIVE BEAM PROFILE MONITORING SYSTEM FOR MUON G-2/EDM EXPERIMENT AT J-PARC*

C. Sung, M. Chung†
Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea
Selcuk Haciomeroglu, Yannis K. Semertzidis[1]
Institute for Basic Science, Daejeon, Republic of Korea
[1]also at Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

Abstract

The muon g-2/EDM experiment at J-PARC aims to measure the muon magnetic moment anomaly, a_μ and electric dipole moment, d_μ by introducing an approach excluding any electric field with measurement goal of 450 and 70 ppb for statistical and systematic uncertainties of a_μ, respectively, and sensitivity of 1.5×10^{-21} e $\cdot$ cm for d_μ. In order to match the phase space and acceptance for injection, the beam needs to be manipulated such that the X and Y components are coupled by means of skew quadrupole magnets through the transmission line. The XY coupling quality can affect the transmission and storage efficiency so that its failure causes systematic error. Since it is significant to monitor the XY coupling status during the beam operation, a non-destructive beam profile monitoring system is under development to investigate the XY coupling quality so as to reduce the source of systematic uncertainties. The device consists of stripline electrodes installed with 45° rotational symmetry. It will reconstruct the coupling parameters such as skew angle and beam size defined as $\sigma_x^2 - \sigma_y^2$ by using multipole analysis of image current. This work presents the simulation result on the reconstruction and the wire test result for the prototype device.

INTRODUCTION

The J-PARC is constructing a beamline described in Fig.1 to measure the electric dipole moment and anomaly of magnetic dipole moment of muon particle with high precision of 70 and 450 ppb, respectively, by producing reaccelerated thermal muon beam which has extremely small emittance of about 1.5π mm $\cdot$ mrad and momentum spread, $\delta p_t/p$, less than 10^{-5} [1].

The muons are required to have a small transverse emittance and the J-PARC has presented the first muon acceleration with a radio-frequency accelerator [2]. The reaccelerated muon beam is injected into the storage magnet after manipulating the phase space for the correlation of horizontal and vertical space, called an XY coupling, to prevent the vertical divergence of beam at the storage section which could be a source of systematic uncertainties on the measurement precision [3].

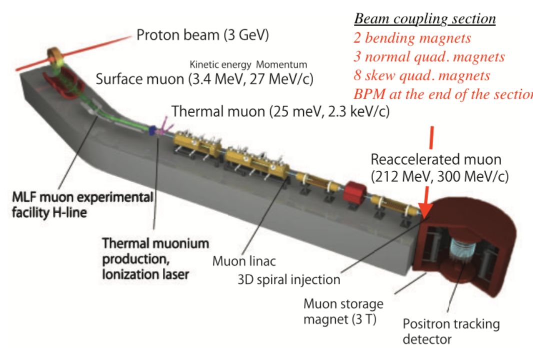
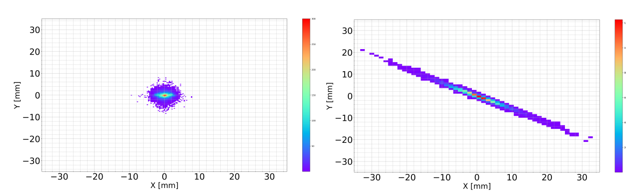


Figure 1: Schematic diagram of J-PARC muon g-2/EDM beam line. A muon beam is produced by using the laser ionization of Muonium and then accelerated through LINAC to $\beta \sim 0.94$. In the end, muons are injected into the solenoidal storage magnet after phase space manipulation by a series of skew quadrupole magnets which are not shown [1].



(a) (b)

Figure 2: Beam distribution in real space (a) at the exit of LINAC where the distribution is azimuthally symmetric and (b) at the injection point after XY coupling.

Thus, the quality of XY coupling needs to be monitored for the beam transportation during a beam-operation to decrease the possible systematic uncertainties. A stripline beam position monitor would be implemented to reach the requirement of monitoring the XY coupling. The features of XY coupling such as the asymmetry of beam size and skew angle would be reconstructed by a method based on the multipole analysis of image currents over the circumference of vacuum chamber.

This paper will present on the multipole analysis of image currents for the method of how the XY coupled beam could be reconstructed. Next section, the mechanical dimension of prototype device will be shown and the wire test result

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† mchung@unist.ac.kr

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will be followed. It will conclude with summary and future plan.

MULTIPOLE ANALYSIS OF IMAGE CURRENT ON CYLINDRICAL CHAMBER

Multipole Analysis

As a charged particle travels through a cylindrical vacuum chamber, it induces an image current over a circumference that is described as the Eq. (1) [4].

$$J(\rho,\phi,R,\theta) = \frac{j(\rho,\phi)}{2\pi R}\left[1+2\sum_{n=1}^{\infty}\left(\frac{\rho}{R}\right)^n \cos\{n(\phi-\theta)\}\right]. \quad (1)$$

A particle beam is usually considered as having Gaussian distributions along two orthgonal directions in a transverse plane so that the image current follows the form of Eq. (2) just like [5].

$$\begin{aligned} J(R,\theta) &= \frac{(I_b/2\pi R)}{2\pi\sigma_x\sigma_y}\int\int dxdy\left[1+\frac{2}{R}(x\cos\theta+y\sin\theta)\right. \\ &\left.+\frac{2}{R^2}\{(x^2-y^2)\cos 2\theta+2xy\sin 2\theta\}\right] \\ &\times\exp\left\{\frac{-(x-x_0)^2}{2\sigma_x^2}\right\}\exp\left\{\frac{-(y-y_0)^2}{2\sigma_y^2}\right\}. \end{aligned} \quad (2)$$

By integration, the equation turns out to be a series of cosine functions as Eq. (3) with parameters of a beam position (ρ_0,ϕ_0) and, rms size $\sigma_x^2-\sigma_y^2$ and skew beam angle, ϕ_2. The image currents are measured at the several locations with a certain rotation symmetry, then, eventually, the measurement will have a periodic form depending on the multipole moment of beam so that the beam coordinate information will be reconstructed by fitting the periodic one to the sinusoidal function.

$$\begin{aligned} J(R,\theta) &= \frac{I_b}{2\pi R}\left[1+\frac{2\rho_0}{R}\cos(\theta-\phi_0)+\frac{2\rho_0^2}{R^2}\cos(2\theta-2\phi_0)\right. \\ &\left.+2\frac{\sigma_x^2-\sigma_y^2}{R^2}\cos(2\theta-2\phi_2)\right]. \end{aligned} \quad (3)$$

Simulation

The reconstruction method was applied to the distribution at the exit of skew magnets in Fig. 2(b). The simulation results in the Fig. 3 that shows the features of coupled beam are well-reconstructed with a good agreement.

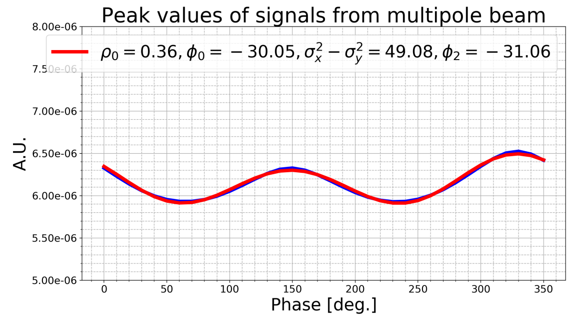

Figure 3: Image currents from the beam distribution of Fig. 2(b).

DESIGN AND WIRE TEST OF PROTOTYPE BPM WITH 4 STRIPLINE

Design of Stripline BPM

The muons are accelerated to the relativistic level ($\beta \sim 0.94$) through the LINAC at the J-PARC beamline. Stripline BPMs are known as well-suited for the relativistic beam of short bunch length [6]. Since the muons travel at the speed of light in the intermediate section between LINAC and storage magnet where the monitor will be implemented, the stripline BPM has been chosen to be used. The striplines were designed by following the beam parameters as shown in the Table 1 by means of the CST Particle Studio.

Table 1: Muon Beam Parameters for J-PARC g-2/EDM Experiment [1]

Beam parameters	
# of muon per bunch	$\sim 10^4$
# of bunch per pulse	2 ~3
Bunch-to-bunch spacing	~3 ns (324 MHz)
Repetition rate of pulse	25 Hz (40 ms)
Long. size (FWHM)	~10 ps
γ (β)	3 (~0.94)

The prototype BPM has been fabricated with 4 striplines shown in Fig. 4 by matching the characteristic impedance to 50 Ω with dimensions as below:

- Chamber diameter: 80 mm.
- Stripline radius: 38 mm.
- Opening angle of stripline: 16°.
- Stripline length: 230 mm.
- End-to-end length: 290 mm.

Following the beam parameters and dimension of electrode, the beam signal is expected to have as $\sim 10^2$ µV for the peak intensity in time domain. Also, it is expected to be about 1 mm for position resolution with an electronics system of 500 MHz bandwidth.

Wire Test

The prototype BPM has been tested with single- and double-path wire which can emulate a signal of beam having dipole and quadrupole moments as shown in the Fig. 5 and Fig. 6.

Using a single path wire which corresponds to the off-centred beam signal, this bench test system was demonstrated if it can properly generate the desired signal. Figure 7(a) shows that this system can properly provide the

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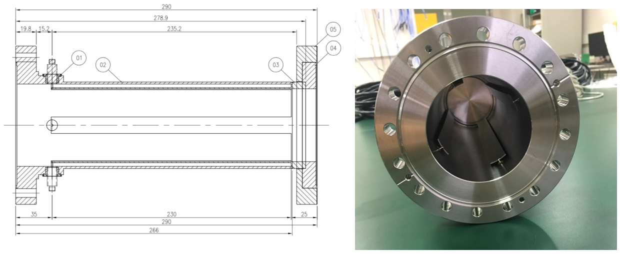
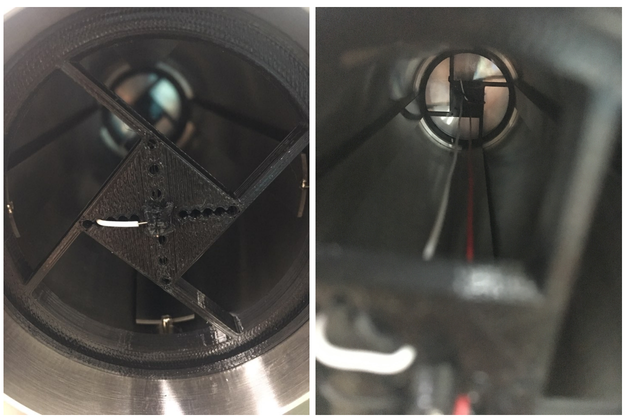


Figure 4: Mechanical drawing and a fabricated prototype BPM.



(a) (b)

Figure 5: Wires to emulate the signal of beam with (a) dipole and (b) quadrupole moments.

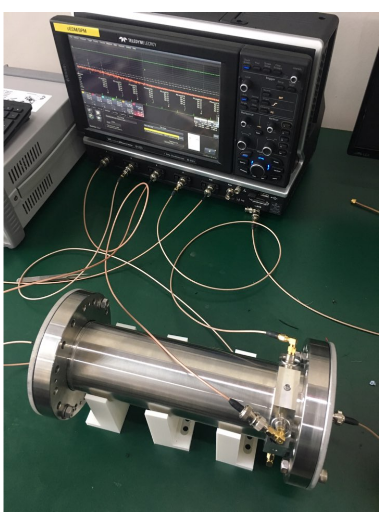
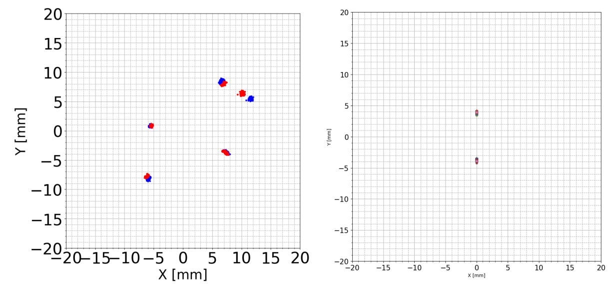


Figure 6: A whole setup for the wire test is shown. Voltage signals are supplied to the wires through a coaxial cable. Responses of striplines are transferred to the oscilloscope.

signal at the desired location where blue for the wire position and red for the reconstruction. Then, the quadrupole moment was excited with double wires at a fixed separation and varying skew angles. As a result, the size of quadrupole moment was well reconstructed while the skew angle was remained unknown because of the lack of number of striplines.



(a) (b)

Figure 7: Results of wire test using multiple wire setup.

CONCLUSION

An XY coupling beam is desired for the muon g-2/EDM experiment at J-PARC. A stripline-based beam profile monitor is under development with a proper reconstruction method. A prototype beam monitor with 4 striplines has been fabricated and tested with conducting wires for detecting an interrelation of transverse space of beam distribution. In order to measure beam coupling properties more precisely, a new device with 8 striplines will be produced [7] and tested with electron beam at the Pohang Light Source II (PLS-II) in 2020. A dispersive beam will be provided from the vertical bending section at PLS-II (Fig. 8).

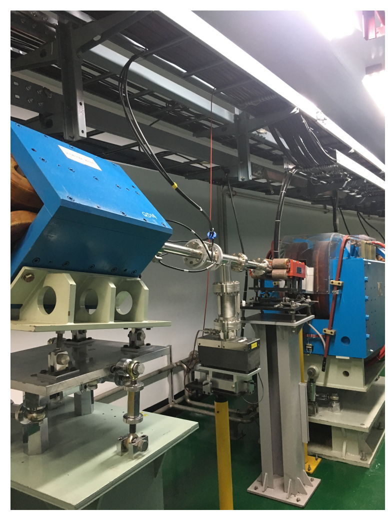


Figure 8: Vertical bending section at PLS-II.

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