Prepared for submission to JINST

The low energy muon beam profile monitor for the muon $g-2$/EDM experiment at J-PARC

Georgiy P. Razuvaev[a,b,1], **Sunghan Bae**[d], **Huynsuk Choi**[d], **Seonho Choi**[d], **Ho San Ko**[d], **Bongho Kim**[d], **Ryo Kitamura**[e], **Tsutomu Mibe**[c] **and Masashi Otani**[c]

[a] *Budker Instute of Nuclear Physics, SB RAS,*
11, akademika Lavrentieva prospect, Novosibirsk, 630090, Russia

[b] *Novosibirsk State University,*
2, Pirogov street, Novosibirsk, 630090, Russia

[c] *KEK,*
Tsukuba, Ibaraki, Japan

[d] *Seoul National University,*
Seoul, South Korea

[e] *University of Tokyo,*
Tokyo, Japan

E-mail: G.P.Razuvaev@inp.nsk.su

Abstract: The muon $g-2$/EDM experiment at J-PARC aims to measure the muon anomalous magnetic moment and electric dipole moment with high precision by utilising an ultracold muon beam. The current muon $g-2$ discrepancy between the Standard Model prediction and the experimental value is about 3.5 standard deviations. This experiment requires a development of the muon LINAC to accelerate thermal muons to the 300 MeV/c momentum. Detectors for beam diagnostics play a key role in such an experiment. The beam profile monitoring system has been designed to measure the profile of the low energy muon beam. It was tested during two beam tests in 2016 at the MLF D2 line at J-PARC. The detector was used with positive muons, $\mathrm{Mu}^-(\mu^+e^-e^-)$, p and H^-, e^- and UV light. The system overview and preliminary results are given. Special attention is paid to the spatial resolution of the beam profile monitor and online monitor software used during data taking.

Keywords: Beam-line instrumentation

[1] Corresponding author.

Contents

1 Introduction

The current muon $g-2$ discrepancy between the Standard Model prediction and the experimental value is about 3.5 standard deviations [1]. The experimental value is almost completely determined by the results of the BNL E821 experiment [2]. The theoretical prediction is based on the mixture of theory itself and experimental data. Further investigation of the $g-2$ puzzle requires a new generation of experiments and approaches on both sides. Thus there are two upcoming direct measurements of $(g-2)_\mu$ under preparation, one at Fermilab [3] — the successor of E821 and another at J-PARC relying on the novel technique described below.

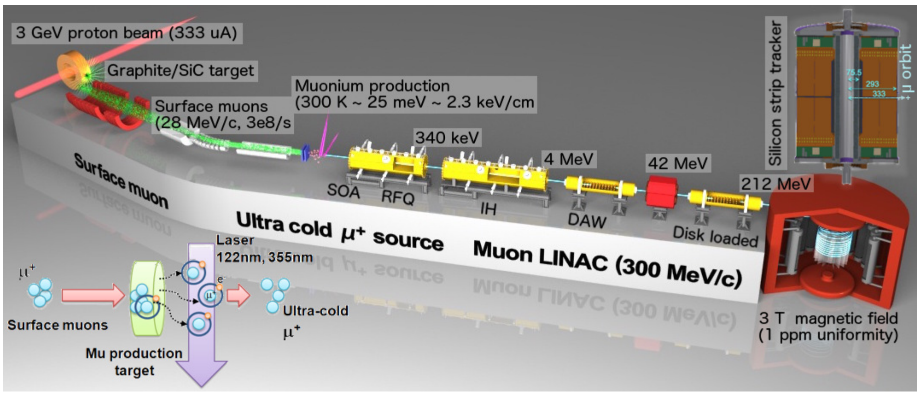

Figure 1: Sketch of the muon $g-2$/EDM experiment at J-PARC.

The muon $g-2$/EDM experiment at J-PARC (E34) aims to measure the muon anomalous magnetic moment and electric dipole moment with high precision by utilising an ultracold muon beam technique [4]. The sketch of the experimental setup is presented in figure 1. The primary 3 GeV proton beam produces surface muons at a graphite target. These muons are transported to a laser-ablated silica aerogel target for muonium production. Diffusing downstream room temperature neutral muoniums experience ionisation via $1S - 2P$ transition by 122 nm and 355 nm laser. Remaining ultracold muons are spirally injected into a storage magnet after passing a linear accelerating tract. Here muons decay and positrons from this decay hit an inner strip silicon track detector, which allows one to reconstruct the e^+ origin, direction and energy. This information is used to measure the muon anomalous magnetic moment and look for the muon electric dipole moment violation from zero.

The E34 experiment requires a linear accelerator for the slow muons to increase their longitudinal momentum up to 300 MeV/c and keep transverse motion as small as possible in a timely manner because of a short muon lifetime [5]. After muonium ionisation the 5.6 keV potential is applied within a SOA lens to stream ultracold muons into the RFQ which forms bunches with a kinetic energy of 340 keV. Then the beam passes through the interdigital H-mode drift tube linac with an output $E_K = 4$ MeV and further flies into the middle- and high-β sections. Experimental tests are going step by step to validate the design of the accelerator. In particular, muon beam tests were conducted to understand the beam parameters after the SOA lens.

Detectors for beam diagnostics play a key role in understanding beam and accelerator parameters. The beam profile monitoring system (BPM) based on a multichannel plate (MCP) and optical readout has been designed to measure the profile of the low energy muon beam. The BPM was tested during two beam tests in 2016 at the MLF D2 line at J-PARC. The detector was used with positive muons, $\mathrm{Mu}^-(\mu^+e^-e^-)$, p and H^-, e^- and UV light.

The expected beam transverse size in the E34 should be about several millimetres. Therefore the spatial resolution of the monitor must be no less than 0.5 mm. To check the resolution, the sharp knife edge procedure was applied.

To perform the beam tests the data acquisition system has been developed and successfully used. Along with that the online monitoring software was used to validate collected data quality in situ.

The system overview and preliminary results are given. Special attention is paid to the spatial resolution of the beam profile monitor and online monitor software used during data taking.

2 Setup

2.1 Beam profile monitor

The low-energy muon BPM core is the two-stage MCP bombarded with particles which give rise to electron avalanches. The latter strike a phosphor screen placed right behind the MCP plates. The screen and MCP are the F2225-21P Hamamatsu assembly. Excited ^{47}Ph is glowing and this is recorded by the CCD camera. Acquired shots are saved in a computer for subsequent analyses. The MCP and Ph screen are situated inside a vacuum vessel, but the camera is placed outside and sees the Ph screen through a window. The camera is pco.1600 produced by PCO company and supplied with the Zeiss Distagon T* 2/28 lens for focusing. The main parameters of the camera and lens are presented in table 1. During the beam test pictures were taken with a 800×600 pixel resolution with the 0.5 μs exposure time in a 2-ADC reading mode. Such settings are optimal for the 25 Hz beam repetition rate and the ^{47}Ph 10 % decay time of 0.11 μs.

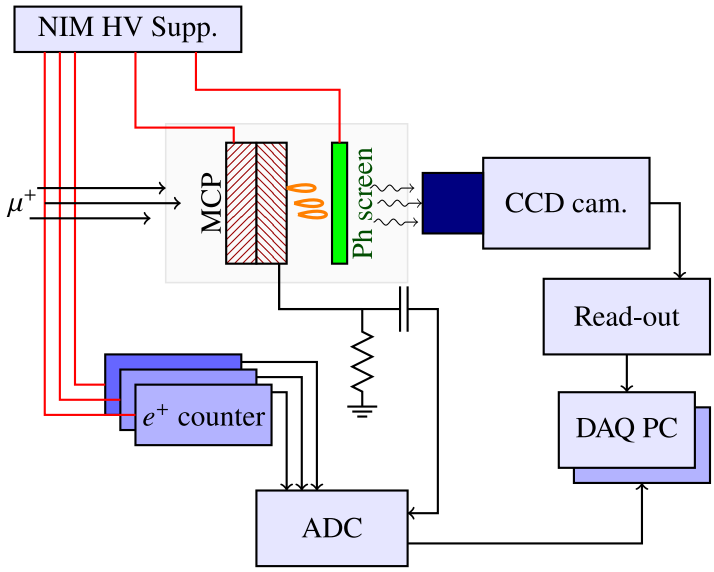

Figure 2: The sketch of the muon $g-2$/EDM experiment at J-PARC.

Table 1: Main BPM parameters.

Parameter	Value
MCP gain	1×10^7 @ 2 kV
Dynamic range	14 bit cooled
Maximum image rate	30 fps @ full 1600×800 resolution
Effective MCP diameter	42 mm
^{47}Ph to CCD cam. QE	28.6 %

The BPM is supplied with a positron counter. It was used for a BPM linearity check [6] and background estimation. The counter consists of three plastic-scintillator tiles, each mounted on a photomultiplier tube. The signal from PMTs is digitised and then studied offline.

2.2 Accelerator

Beam tests were conducted at J-PARC at the Material and Life science Facility (MLF) using MUSE tools. A 3 GeV proton beam is used to produce surface muons with a graphite target with a repetition rate of 25 Hz. Such muons are collected and passed to the D2 beam line. This line provides μ^+ allowing one to choose momentum up to 50 MeV/c. The output beam intensity is 3×10^6 μ^+/s at the 200 kW p beam.

The diagnostic beam line serves to measure the effect of an electrostatic SOA lens on the beam dynamics. The SOA lens is using a 20 kV electric potential to focus slow particles produced at a target. Here a thin aluminium foil is used as a test substitution for the aerogel target with laser ionisation. The Al foil transforms surface muons to epithermal Mu$^-$. After focusing, particles pass trough an electrostatic deflector, electric quadrupoles and bending magnet, and hit a diagnostic system such as the BPM or a single-anode MCP (see figure 3). The latter is used as a time-of-flight and particle rate measurement system.

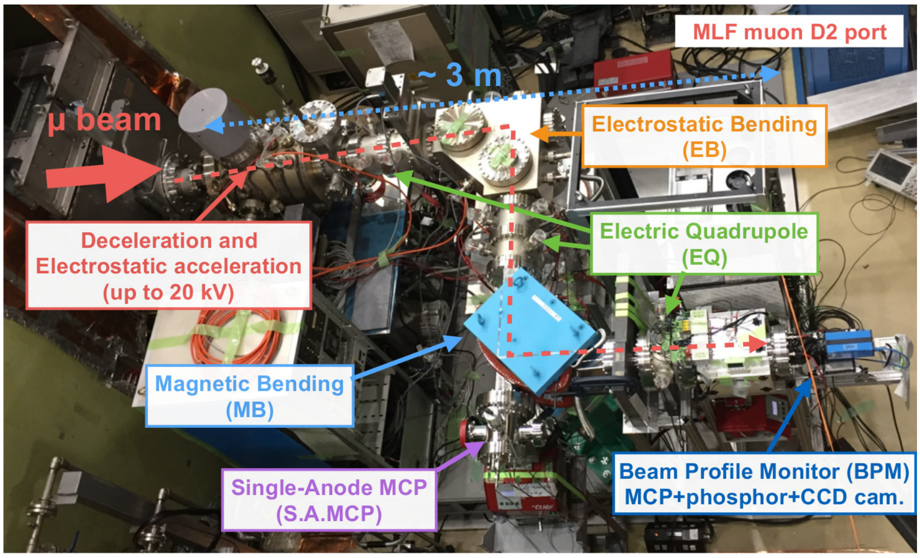

Figure 3: The diagnostic beam line at the D2 port at the MLF, J-PARC.

3 Spatial resolution measurement

The beam profile monitor has been designed to measure parameters of a low energy muon beam. The monitor aim is to allow one tuning and investigation of low β accelerator parts and production of μ^+ at aerogel. To do that it is necessary to measure a beam profile not only in a transverse plane, but also along the beam axis. The expected beam transverse size should be about several millimetres. Therefore the spatial resolution of the monitor must be not worse than 0.5 mm. To check the resolution, the sharp knife edge procedure was applied [7].

Figure 4: The collimator

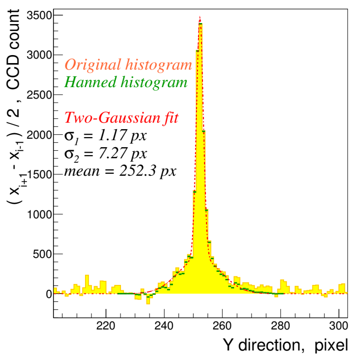

Figure 5: The line spread function.

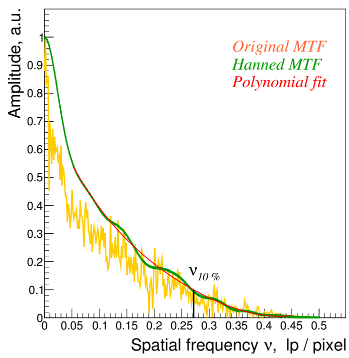

Figure 6: The modulation transfer function.

The half-open circular-hole collimator (see figure 4) was mounted as close as ~1 cm to the MCP surface. The set of pictures was taken with a UV light source. To reduce the fluctuation in every pixel the pictures were averaged. The picture was rotated to make horizontal alignment of the edge. 1 pixel-thick Y projections are formed, i.e. they are knife edge pictures. Discrete differentiation is applied to the projection, the result is the line spread function (LSF). The LSF is multiplied by the Hann window to enhance the peak correspondingly at the collimator edge. An additional suppression of signal fluctuation outside the peak is used. The result window function is the following

$$f = \begin{cases} 0.5 - 0.5\cos\left(\frac{2\pi(n-n_0)}{M-1}\right) & \text{if } n \text{ is inside the peak area,} \\ 0 & \text{otherwise,} \end{cases}$$

where n is the index of pixel, n_0 — the index of the first pixel in the edge peak area, M — the length of the peak area. The obtained distribution is fitted with the sum of two Gaussians to calculate the FWHM, an example is presented in figure 5. To get the modulation transfer (MTF) function, the FFT is applied. The MTF is approximated with a polynomial as shown in figure 6, then $\nu_{10\,\%}$, the position of the 10 % height, is determined. The correctness of the MTF evaluation is proved by matching the $\nu_{10\,\%}$ and inverted FWHM values. The spatial frequency $\nu_{10\,\%}$ is converted to the spatial resolution by applying 77.8 µm/pixel, the conversion factor from CCD camera pixels to distance. So far the spatial resolution is measured to be (294 ± 1) µm.

4 DAQ and on-line monitoring system

The DAQ system of this monitor consists of the CCD camera and several computers to collect, store and analyse data. The CCD camera is coupled with a block which provides power supply and image capturing measurement. This block is connected to the Windows machine with PCO software installed. The software allows one to adjust camera parameters, operate data taking etc. During beam tests the camera is fired by the beam arrival signal with a preliminary set time offset to match the beam arrival time to the MCP. Commonly the set of 10000 pictures is recorded as a single file with a unique name at a shared directory of a Linux analysing machine. An operator fills a line in the log file with information about the setup, e.g. camera exposure time. There are several constantly running scripts on the Linux computer performing several functions. The first script is watching for appearance of a new raw file with photographs and when its size becomes stable, which signals that taking the set of pictures is completed, copies it to the external disk space. When a reserve copy of the raw file is ready, the second script initiates its conversion to the ROOT file data format. During this procedure every picture is cropped to 600 × 600 pixels without damage of the Ph screen image. Also the data stamp is moved from the top left corner close to the Ph screen. The third script analyses the converted file. For high beam intensity the general distribution analysis is performed. For every picture it calculates a mean value, RMS, skewness, kurtosis, search peak position and average pictures. In case of low intensity the analysis is concentrated on single peak finding, determining its position, integral intensity and peak value. The operator can use a macros to produce a set of plots displaying analysis results for easy understanding of data quality and beam parameters. A typical data cycle with 10000 pictures takes about 10 minutes.

5 Conclusion

The new muon $g-2$/EDM measurement in J-PARC requires development of the muon beam line, which is impossible to imagine without beam diagnostic systems. Such a system based on the

MCP, Ph screen and CCD camera readout was created and its performance was demonstrated in a couple of beam tests at the MLF J-PARC with a low energy muon beam. In this work the BPM spatial resolution was measured with the sharp knife edge technique to be $(294 \pm 1)\,\mu\mathrm{m}$, and data acquisition with the online monitoring system was made. Now the BPM is successfully helping in muon linac development.

Acknowledgments

We thank the J-PARC personal for excellent machine operation. The MCP assembly and CCD camera procurement and beam test preparation are supported by the Korean National Research Foundation grant NRF-2017R1A2B3007018. Work on the monitor software is partially supported by the Russian Foundation for Basic Research grant RFBR 17-52-50064, work on the beam profile monitor spatial resolution measurement is partially supported by the Russian Science Foundation grant RNF 17-12-01036.

References

[1] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, *$(g-2)_\mu$ and $\alpha(M_Z^2)$ re-evaluated using new precise data*, *J. Phys.* **G38** (2011) 085003, [1105.3149].

[2] Muon g-2 collaboration, G. W. Bennett et al., *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, *Phys. Rev.* **D73** (2006) 072003, [hep-ex/0602035].

[3] Muon g-2 collaboration, J. Grange et al., *Muon (g-2) Technical Design Report*, 1501.06858.

[4] J-PARC g-2/EDM collaboration, N. Saito, *A novel precision measurement of muon $g-2$ and EDM at J-PARC*, *AIP Conf. Proc.* **1467** (2012) 45–56.

[5] M. Otani et al., *Development of Muon LINAC for the Muon g-2/EDM Experiment at J-PARC*, in *Proceedings, 7th International Particle Accelerator Conference (IPAC 2016): Busan, Korea, May 8-13, 2016*, p. TUPMY003, 2016. DOI.

[6] H. Choi, "Linearity analysis on low energy muon beam profile monitor." E34-REPORT-0004.

[7] G. P. Razuvaev, "The spatial resolution study of the low energy muon beam profile monitor." E34-NOTE-0021.