12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB325

DEVELOPMENT OF BUNCH WIDTH MONITOR WITH HIGH TIME RESOLUTION FOR LOW EMITTANCE MUON BEAM IN THE J-PARC MUON g-2/EDM EXPERIMENT

M. Yotsuzuka*, T. Iijima[1], K. Inami, Y. Sue, K. Sumi, Nagoya University
M. Otani, T. Mibe, KEK, Tsukuba, Ibaraki 305-0801, Japan
Y. Kondo, JAEA, Tokai, Naka, Ibaraki 319-1195, Japan
N. Saito, J-PARC Center, Tokai, Naka, Ibaraki 319-1195, Japan
Y. Takeuchi, Kyushu University, Fukuoka, 819-0395, Japan
Y. Nakazawa, Ibaraki University, Mito, Ibaraki 310-8512, Japan
H. Yasuda, University of Tokyo, Hongo, Tokyo 171-8501, Japan
[1]also at KMI Nagoya University, Nagoya, Aichi 464-8602, Japan

Abstract

The J-PARC E34 experiment plans to measure the muon anomalous magnetic moment and electric dipole moment sensitive to new physics with high precision. This experiment uses a novel method using the low-emittance muon beam achieved by cooling and re-acceleration. In the muon linac consisting of four different accelerating cavities, the main cause of the emittance growth is the beam mismatch between the different cavities. Especially for the cavity in the low-beta section (β = 0.08 to 0.27), the longitudinal acceptance is narrow and beam mismatch has a significant impact on the entire linac. Therefore, we developed a bunch width monitor (BWM) using a microchannel plate (MCP), which can measure the low-emittance muon beam with high time resolution. The time resolution of the BWM was measured to be 40 ps on the test bench using a picosecond pulse laser. We also evaluated factors that limit the current time resolution. In this paper, the results of the evaluation of the BWM are reported.

INTRODUCTION

The muon anomalous magnetic moment ($g-2$) has high sensitivity to various quantum effects, so it has attracted attention as a probe for investigating a new physics. The results of the Brookhaven National Laboratory (BNL) E821 experiment with a precision of 0.54 ppm show a deviation of more than 3σ from the theoretical value calculated from the standard theory, which is expected to be a sign of new physics [1,2]. Furthermore, the values reported by the Fermi National Laboratory (FNAL) E989 experiment also support this result [3]. However, since these previous experiments use the same measurement method, it is needed that verification experiments using different methods.

The J-PARC E34 experiment focused on improving the muon beam quality, which is the main source of systematic errors in the BNL E821 experiment [4]. Especially, we use the low-emittance muon beam, in which beam spread is very narrowed by cooling and re-acceleration. In this experiment, we improve the systematic errors from 0.21 ppm in the BNL E821 experiment to less than 0.07 ppm, aiming for a precise measurement of muon $g-2$ with an accuracy of 0.1 ppm. At the same time, we would like to search for the muon electric dipole moment (EDM) with a sensitivity of 10^{-21} e · cm, which related to the CP violation of leptons.

Development of a Muon Linear Accelerator

The ultra-slow muons are generated by cooling the surface muons to 25 meV. Then in order to rapidly accelerate them to 212 MeV, it is essential to realize muon radio frequency (RF) acceleration which is unprecedented. In addition, in order to cope with the rapid velocity changes associated with acceleration, we are developing a muon linear accelerator (linac) consisted of four different acceleration cavities depending on the energy (Fig. 1). The requirements of the muon beam are shown in Table 1.

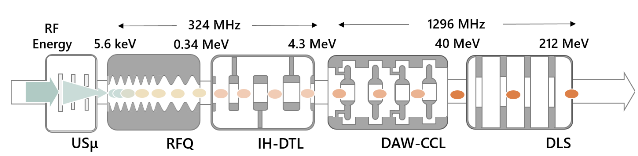

Figure 1: Schematic of the muon linac [4].

Table 1: Requirements at the Muon Linac Exit [5]

Energy	212 MeV
Normalized transverse emittance	1.5 π mm mrad
Momentum spread	0.1%

The main cause of emittance increase in a muon linac is beam mismatch between different acceleration cavities. On the other hand, the design prioritizes acceleration efficiency in the low energy section, because the effect of muon lifetime decay is more pronounced. Therefore, there is a problem that the IH-DTL adopting the alternative phase focusing (APF) scheme has very narrow longitudinal acceptance [6]. As shown in Fig. 2, if the muon beam emitted from the RFQ is directly injected into the IH-DTL, it is expected to occur a serious beam mismatch. As a result, the longitudinal

* yotsuzuka@hepl.phys.nagoya-u.ac.jp

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB325

emittance growth becomes more than 100% compared to the RFQ exit.

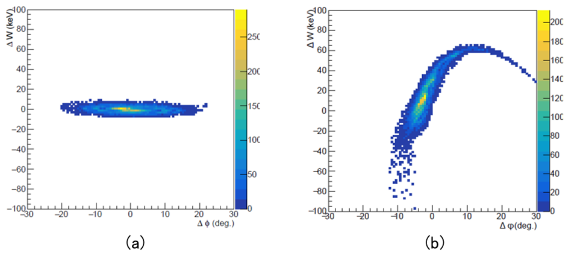

Figure 2: Expected beam distribution in the longitudinal direction by simulation. (a) At the RFQ exit. Bunch width is about σ = 60 ps. RMS emittance is 0.018 π mm mrad. (b) At the IH-DTL exit. Serious emittance increase has occurred.

BEAM MATCHING

Beam matching based on measurements between different acceleration cavities is important to suppress the emittance growth during transport. Therefore, we have designed a beam transport line consisting of diagnostic systems and optical systems, based on the evaluation in the simulation. It is shown in Fig. 3.

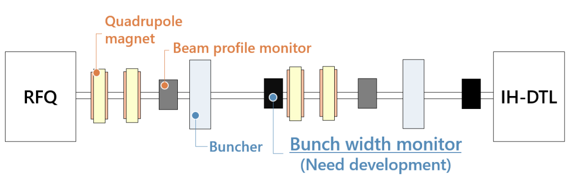

Figure 3: Schematic of the beam transport line between the RFQ and the IH-DTL.

When beam matching is performed in this transport line through diagnostics and shaping, the longitudinal emittance increase due to IH-DTL acceleration can be suppressed to less than 40% which satisfies the requirement of the experiment. However, in order to meet this, a beam monitor capable of measuring low emittance muon beam with high accuracy is required. A beam profile monitor (BPM) with a position resolution of 0.3 mm has already been developed for the transverse measurement [7].

The bunch width monitor (BWM), which measures the longitudinal direction, is needed to have a high time resolution of 40 ps which corresponds to an accuracy of approximately 1% of the acceleration phase 324 MHz. In the demonstration test, the beam intensity is limited by the ultra-slow muon source and expected to be order of a single muon per pulse, so that it is also required to be able to detect low-intensity muon beams. In order to satisfy these two requirements, we are developing the BWM with a micro channel plate (MCP) which has high time resolution and high sensitivity to a single muon [8, 9].

Design of the Bunch Width Monitor

A schematic diagram of the BWM is shown in Fig. 4.

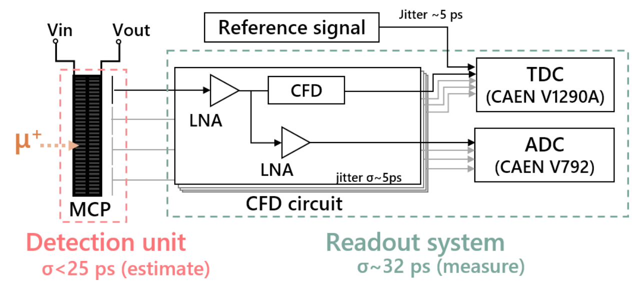

Figure 4: Schematic diagram of the BWM.

We use a multi-anode MCP assembly (Hamamatsu photonics (F1217)) shown in Fig. 5 for the detection unit. It detects muon directly using secondary electron amplification, and has a high responsiveness. The effective area is 42 mm in diameter. It has two layer stages, and typical gain of 10^6–10^7. The channel diameter is 12 μm, and the bias angle of the channel is 12°. The anode is divided into four to suppress the effect of momentum dispersion when the demonstration test.

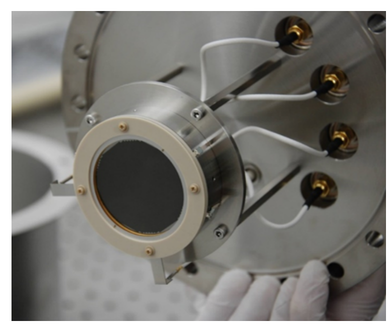

Figure 5: Photo of the MCP.

We introduce a CFD circuit after the MCP, and it can suppress the degradation of time resolution that depends on the signal wave height. Then, the ECL signal output from the CFD circuit is read by the TDC CAEN V1290A to obtain the time information. In the same way, the charge information is obtained from the analog signal using ADC CAEN V792.

From previous evaluations, it is revealed that the readout system has a time resolution of about σ = 32 ps. On the other hand, the exact performance of the MCP is not understood. If the resolution of MCP is less than 25 ps as expected from previous studies of MCP-PMT, the BWM can achieve the required resolution of less than 40 ps.

PERFORMANCE EVALUATION

We have developed a test bench using picosecond pulsed lasers [9]. As shown in Fig. 6, the laser is irradiated on the surface of the MCP to cause a photoelectric effect, and the photoelectrons produced are used to evaluation.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB325

As a result, we obtained 47 ps as the measured value (Fig. 7). However it also includes the factor relates to the test bench. Therefore, in order to clarify the performance of the BWM consisting of the MCP and the readout system, the elements included in the measured values were classified. The results are shown in Table 2. The performance of the picosecond pulse laser is referred to result of evaluation requested from Hamamatsu Photonics.

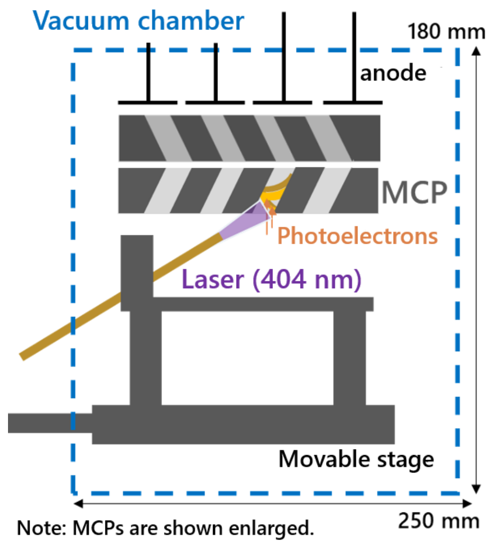

Figure 6: Configurations of the test bench.

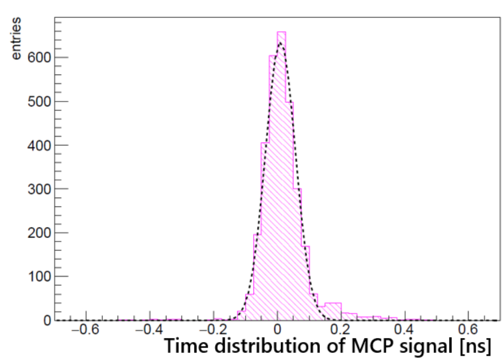

Figure 7: Time distribution of MCP signal. It is eliminated crosstalk.

Table 2: Classification of Measurement Result

	σ (ps)	
total	47	Measure
picosecond pulse laser	24	Evaluate
BWM	40	Estimate
Readout system	32	Measure
MCP	<25	Estimate

We revealed that the time resolution of the BWM is 40 ps, which achieved the required time resolution. In addition, we showed the performance of the MCP is consistent with expectations from previous studies. We need to study the effects of the readout system and the laser in more detail to reveal the exact performance of the MCP.

Considerations for Time Resolution Limitations

As shown in Fig. 8, we evaluated the wave height dependence of the time resolution. In addition to the standard measurements, we applied a higher voltage to the first stage of MCP to investigate the higher charge amount region. Look at 30 pC and above, there is a limit of time resolution. Based on the discuss on the Table 2, we are considering the readout system and laser as the cause of this. As a prospect, we select and evaluate a waveform readout digitizer with DRS4 to further improvement of the BWM.

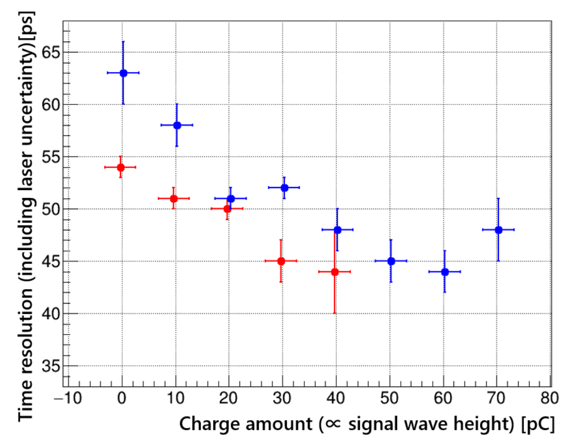

Figure 8: Wave-height dependence. The horizontal axis represents the amount of charge and the vertical axis represents the time resolution including laser uncertainty. The red dots indicate the case when applied voltage to the MCP first stage is standard (-2300 V), and the blue dots indicate the case when applied higher voltage (-2740 V).

CONCLUSION

We have developed the BWM with high time resolution for the J-PARC E34 experiment. Since we use MCP for detection unit of BWM, it capable of measuring low emittance muon beams with high time resolution. We have guaranteed that the time resolution of the BWM is σ = 40 ps from the evaluation by the test bench. In addition, we revealed it enable achieving higher time resolution with improvements of the readout system and laser.

The first ultra slow muon acceleration and emittance measurement plan to perform at 2022. We would like to optimize the BWM to use in real beam line.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Numbers JP15H03666, JP15H05742, JP16H03987, JP16J07784,JP18H03707, JP18H05226, and JP20H05625.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB325

REFERENCES

[1] G. W. Bennett *et al.*, "Final report of the E821 muon anomalous magnetic moment measurement at BNL", *Phys. Rev. D*, vol. 73, no. 7, p. 072003, 2006. doi:10.1103/PhysRevD.73.072003

[2] T. Aoyama *et al.*, "The anomalous magnetic moment of the muon in the Standard Model", *Phys. Rep.*, vol. 887, pp.1–166, 2020. doi:10.1016/j.physrep.2020.07.006

[3] B. Abi *et al.*, "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm", *Phys. Rev. Lett.*, vol. 126, no. 14, p. 141801, 2021. doi:10.1103/PhysRevLett.126.141801

[4] M. Abe *et al.*, "A New Approach for Measuring the Muon's Anomalous Magnetic Moment and Electric Dipole Moment", *Prog. Theor. Exp. Phys.*, vol. 2019, no. 5, p. 053C02, 2019. doi:10.1093/ptep/ptz030

[5] Y. Kondo *et al.*, "Re-Acceleration of Ultra Cold Muon in JPARC Muon Facility", *in Proc. IPAC'18*, Vancouver, BC, Canada, Apr.-May 2018, pp. 5041–5046. doi:10.18429/JACoW-IPAC2018-FRXGBF1

[6] M. Otani *et al.*, "Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac", *Phys. Rev. Accel. Beams*, vol. 19, no. 4., p. 040101, 2016. doi:10.1103/PhysRevAccelBeams.19.040101

[7] B. Kim *et al.*, "Development of a microchannel plate based beam profile monitor for a re-accelerated muon beam", *Nucl. Instrum. Meth. A*, vol. 899, pp. 22-27, 2018. doi:10.1016/j.nima.2018.05.014

[8] Y. Sue *et al.*, "Development of a bunch-width monitor for low-intensity muon beam below a few MeV", *Phys. Rev. Accel. Beams*, vol. 23, no. 2, p. 022804, 2020. doi:10.1103/PhysRevAccelBeams.23.022804

[9] M. Yotsuzuka *et al.*, "Development of the Longitudinal Beam Monitor with High Time Resolution for a Muon LINAC in the J-PARC E34 Experiment", *in Proc. IPAC'19*, Vancouver, Melbourne, Australia, May, 2019, pp. 2571-2574. doi:10.18429/JACoW-IPAC2019-WEPGW042