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DEVELOPMENT OF THE DIAGNOSTIC BEAMLINE FOR MUON ACCELERATION TEST WITH APF IH-DTL

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Abstract

The muon-dedicated linear accelerator is being developed for the muon g−2/EDM experiment at J-PARC. To suppress the decay loss during acceleration, the alternating phase focusing (APF) method inter-digital H-mode drift tube linac (IH-DTL) is adopted in the low-velocity region following a radio-frequency quadrupole linac (RFQ). We are planning to accelerate muons in 2025 using the RFQ and the IH-DTL which will accelerate muons from β=0.08 to 0.28 with an operating frequency of 324 MHz. After the IH-DTL, a diagnostic beamline will be placed to measure the beam energy and quality after acceleration, and its design, which consists of magnets and bunchers, is underway. In this poster, we will report on the development status of the diagnostic beamline.

INTRODUCTION

The muon anomalous magnetic moment shows a divergence of 4.2 σ between theoretical and experimental values [1]. For further validation, the muon g-2/EDM experiment is planned at Japan Proton Accelerator Research Complex (J-PARC) to precisely measure the anomalous magnetic moments and the electric dipole moments of the muon [2]. In this experiment, a muon-dedicated linear accelerator consisting of four types of radio-frequency cavities will be used to generate a low-emittance muon beam [3,4]. To suppress the decay loss during acceleration, Inter-digital H-mode Drift-Tube-Linac (IH-DTL) with alternating phase focusing (APF) method is adopted in the low-beta (β=0.08–0.28) section [5]. Because it is the first case to adapt 324 MHz APF IH-DTL for muon acceleration, it is necessary to demonstrate an accelerating muon.

ACCELERATION TEST WITH APF IH-DTL

Acceleration test using the APF IH-DTL will be performed in a setup consisting of an ultra-slow muon source [2], RFQ, transport beamline, IH-DTL, and diagnostic beamline as shown in Fig. 1. In the muon source, a muon beam supplied from the MLF at J-PARC is radiated at a silica aerogel target to convert it into muonium, a bound state of electron and muon. Then, laser irradiation strips electron from muonium to produce ultra-slow muon. The ultra-slow muon beam is accelerated from β =0.01 to 0.08 while being bunched in the RFQ. In the transport line, the beam is shaped to match the acceptance of the IH-DTL using quadrupole magnets and bunchers and accelerated from β=0.08 to 0.28 in the IH-DTL. The beam accelerated in the IH-DTL is diagnosed in the diagnostic beamline. Muon acceleration using an RFQ has been demonstrated [3] with negative muonium ions and acceleration tests of ultra-slow muons are currently underway. The basic design of the beamline to transport and match the beam from the RFQ to the IH-DTL has been completed. The fabrication and the low-power test of the IH-DTL were completed. In order to perform an acceleration test, it is necessary to design diagnostic beamlines to measure the beam emittance and energy after acceleration at the IH-DTL. Table 1 shows the expected beam emittance and energy estimated by simulation.

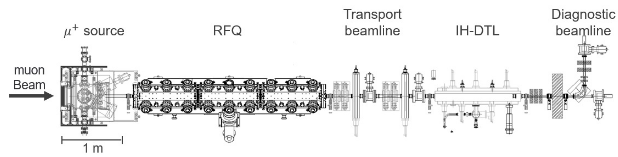

Figure 1: Configuration of acceleration test

Table 1: Ideal Parameters of Muon Beams Accelerated by IH-DTL

Parameters	**Sim.**
Emittance x(unnorm., rms)	1.235 π mm mrad
Emittance y(unnorm., rms)	0.706 πmm mrad
Emittance z(rms)	0.0961 π deg keV
Kinetic energy	4.3 MeV

THE DIAGNOSTIC BEAMLINE

The diagnostic beamline is configured as shown in Fig. 2. The roles of each component are as follows.

- Steering magnet: Correct the trajectory shift in the y-direction by the influence of TE_{11} mode.

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- Quadrupole magnet: Transverse convergence
- Bending magnet: Bend the direction of transport according to the momentum of the particles.
- Buncher: Longitudinal convergence
- Beam Profile Monitor (BPM) [6]: Measure beam profile with Micro Channel Plate (MCP)

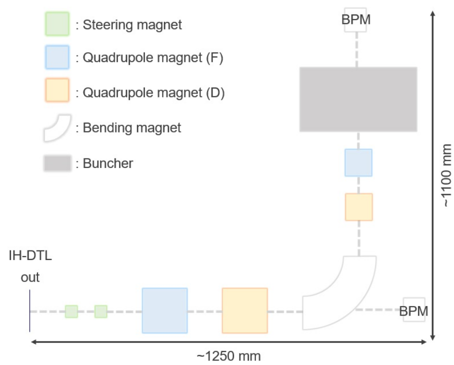

Figure 2: Configuration of the diagnostic beamline

Beam Diagnostic Methods

First, the energy measurement of the accelerated beam is described. There are two ways to check if the beam is accelerated to the target energy (velocity): TOF measurement and energy selection using a bending magnet. The latter is used for this diagnostic beamline for two reasons. Firstly, the space available to install a diagnostic beamline is limited, and it is impossible to place two monitors for TOF measurements. Secondly, for the first attempt at acceleration using IH-DTL, it is desirable to be able to eliminate background in the emittance measurement described below. Therefore, a bending magnet capable of momentum selection is installed in the beamline.

Second, the emittance measurement method is described. Emittance is measured by the Q-scan method using the quadrupole magnets and the buncher installed after the bending magnet in Fig. 2. The Q-scan method measures the beam width changed by varying the convergence force of the quadrupole magnet and calculates emittance from the relationship between the convergence force of the optical system and the beam width. The relationship between the σ matrix, which represents the property of the beam, and the transfer matrix of each component is expressed as the following equation,

$$\sigma_{\text{final}} = R\sigma_{\text{initial}}R^T, \tag{1}$$

where R is the transfer matrix and σ_{initial} is written as

$$\sigma_{\text{initial}} = \begin{pmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} \tag{2}$$

$$\sigma_j = \begin{pmatrix} \sigma_{j11} & \sigma_{j12} \\ \sigma_{j21} & \sigma_{j22} \end{pmatrix} = \begin{pmatrix} \beta_j\varepsilon_j & -\alpha_j\varepsilon_j \\ -\alpha_j\varepsilon_j & \gamma_j\varepsilon_j \end{pmatrix}, \ j = x,\ y,\ z$$

using emittance ε and twis parameters α, β, γ. Since $\beta\varepsilon$ is equal to the square of the beam width, Eq. (1) can be used to derive the relation as follows.

$$\begin{aligned} \sigma_{\text{final},y11} = {} & \sigma_{\text{initial},y11}R_{33}^2 \\ & + 2R_{33}R_{34}\sigma_{\text{initial},y12} + \sigma_{\text{initial},y22}R_{34}^2 \end{aligned} \tag{3}$$

$$\begin{aligned} \sigma_{\text{final},x11} = {} & \sigma_{\text{initial},x11}R_{11}^2 + 2R_{11}R_{12}\sigma_{\text{initial},x12} \\ & + \sigma_{\text{initial},x22}R_{12}^2 + \sigma_{\text{initial},z22}R_{16}^2 \end{aligned} \tag{4}$$

For scanning in the y-direction, emittance can be derived by varying the value of the quadrupole magnet for y-directional focusing without using the buncher. Since the x and z-directions are correlated by the bending magnet, the emittance in the x and z-directions can be measured by measuring the beam width in the x-direction by simultaneously changing the focusing force of the quadrupole magnet and buncher.

RESULTS

Emittance Measurement Accuracy

After determining the components of the diagnostic beamline, the quadrupole magnets and buncher focusing force were optimized in Trace3D [7] to eliminate losses due to the beam pipe up to the BPM and to prevent the beam from spreading too much just before the magnet and buncher where Q-scan is performed. And the beam distribution after steering magnets obtained from beam generation and acceleration simulations was used in the optimization. Table 2 summarizes the results of a simulated scan with General Particle Tracer (GPT) [8] using the optical system determined with Trace3D.

Table 2: Comparison of Ideal Emittance and Scan Results

Parameters	**Simulation Input**	**Scan Results**
Emittance x (unnorm., rms) [π mm mrad]	1.235	1.239 (+0.3%)
Emittance y (unnorm., rms) [π mm mrad]	0.706	0.648 (-8.2%)
Emittance z (rms) [π deg keV]	0.0961	0.0963 (+0.2%)

The Q-scan curve obtained for the y-direction is shown in Fig. 3. Where $\sqrt{|K|}$ is a value proportional to the focusing force of the quadrupole magnet. Fitting using Eq. (3) results in an emittance 8% lower than the simulation input. This is because the beam in the y-direction is shaved off about 1% by the beam pipe, resulting in an underestimation of emittance. The Q-scan curve obtained for the x and z-direction is shown in Fig. 4. By varying the focusing force of both the quadrupole magnet and the buncher, the Q-scan curve is fitted with a bivariate function as in Eq. (4). Where $f(E_0LT)$ is a value proportional to the focusing force of the buncher. The results of the fitting showed that the diagnostic error of emittance was within 1%.

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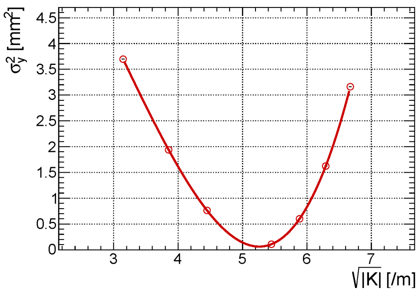

Figure 3: Simulated Q-scan curve in the y-direction.

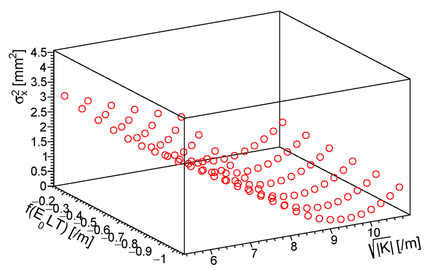

Figure 4: Simulated Q-scan curve in the x and z-direction.

Requirements for Beam Monitor

The requirement of emittance error is less than 10% for the acceleration test [9]. On the other hand, the above evaluation results do not include the resolution of the BPM. The expected measured beam width ($\sigma_{\text{exp.}}$) can be expressed using the expected actual beam width ($\sigma_{\text{sim.}}$) and the monitor resolution (σ_{BPM}) by the following relation,

$$\sigma^2_{\text{exp.}} = \sigma^2_{\text{sim.}} + \sigma^2_{\text{BPM}}. \tag{5}$$

According to Eq. (5), the expected measured beamwidth increases with the resolution of the BPM. In the same method as in the previous section, the emittance is evaluated with the expected measurement beamwidth, and the difference ($\Delta\varepsilon$) from the simulation input is evaluated as shown in Fig. 5. The difference ($\Delta\varepsilon$) increases as the BPM resolution increases.

The measured beam width can be corrected if the BPM resolution is known;

$$\sigma^2_{\text{corr.}} = \sigma^2_{\text{meas.}} - \sigma^2_{\text{BPM}}. \tag{6}$$

The emittance can be evaluated after the correction using $\sigma_{\text{corr.}}$ with the same method. If there is a difference between the estimated and actual BPM resolution, it results in the difference between the evaluated and actual emittance. Because the BPM resolution is evaluated to be 0.3 mm [6], the effect was investigated around its value as shown in Fig. 6. The vertical axis shows the estimated emittance using Eq. (6) assuming $\sigma_{\text{BPM}} = 0.3$ mm, and the horizontal axis of Fig. 6 is the actual BPM resolution. When the actual BPM resolution is the same as the assumed resolution of 0.3 mm, the result is the same as in Table 2. In order to satisfy the requirement for the emittance measurement, the actual BPM resolution should be 0.297–0.313 mm, based on which additional study about the BPM resolution will be conducted.

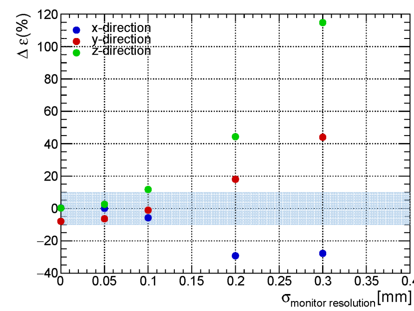

Figure 5: Relationship between monitor resolution and emittance measurement error.

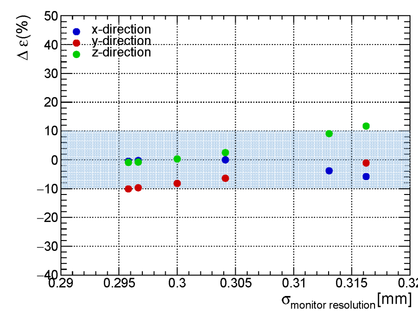

Figure 6: Relationship between true monitor resolution and emittance measurement error when the resolution of the BPM is corrected as 0.3 mm.

CONCLUSION

A diagnostic beamline was designed for the world's first demonstration of the muon acceleration test with IH-DTL. The diagnostic beamline consists of magnets and a buncher, and the muon energy after acceleration can be measured using a bending magnet. In addition, by using quadrupole magnets and buncher together, emittance measurements can be made with an accuracy that meets the requirements. In actual measurements, the position resolution of the monitor must be taken into account, and a detailed evaluation of the resolution is required.

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REFERENCES

[1] B. Abi *et al.*, "Measurement of the positive muon anomalous magnetic moment to 0.46 ppm", *Phys. Rev. Lett.*, vol. 126, p. 141801, 2021. doi:10.1103/PhysRevLett.126.141801

[2] M. Abe *et al.*, "A new approach for measuring the muon anomalous magnetic moment and electric dipole moment", *Prog. Theor. Exp. Phys.*, vol. 2019, p. 053c02, 2019. doi:10.1093/ptep/ptz030

[3] M. Otani, "First muon acceleration and muon linear accelerator for measuring the muon anomalous magnetic moment and electric dipole moment", *Prog. Theor. Exp. Phys.*, vol. 2022, p. 052C01, 2022. doi:10.1093/ptep/ptac067

[4] Y. Kondo *et al.*, "The Muon Linac Project at J-PARC", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 636–641. doi:10.18429/JACoW-LINAC2022-WE1AA05

[5] M. Otani *et al.*, "Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac", *Phys. Rev. Accel. Beams*, vol. 19, p. 040101, 2016. doi:10.1103/PhysRevAccelBeams.19.040101

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

[7] K.R. Crandall and D.P. Rusthoi, "TRACE-3D documentation". 3rd ed., Los Alamos Report No. LA-UR-97-886, 1997.

[8] Pulser Physics, "General Particle Tracer", http://www.pulsar.nl/gpt/.

[9] Y. Nakazawa, "Development of an interdigital H-mode drift tube linac for the J-PARC muon g-2/EDM experiment", Ph.D. thesis, Ibaraki University, Ibaraki, Japan, 2023.