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DEVELOPMENT OF A CHERENKOV RADIATION-BASED BEAM PROFILE MONITOR FOR A MUON LINEAR ACCELERATOR*

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Abstract

In order to test the Standard Model through a precision muon g–2 measurement, the J-PARC muon g–2/EDM experiment is constructing a 212 MeV muon accelerator. In the early stages of commissioning, the number of muons per bunch is expected to be as low as only a few tens, and furthermore, since dark current electrons are mixed into the muon beam, the conventional beam diagnostic methods used in accelerators cannot be applied. We are developing a Cherenkov-type beam monitor that utilizes Cherenkov radiation to selectively measure only muons from a muon beam mixed with dark current. The resolution of the profile was evaluated under ideal conditions without errors, based on the optical design of the detector. We are also investigating radiation hardness of the radiators to be used in the measurements.

INTRODUCTION

To test the Standard Model through precision measurements of the muon anomalous magnetic moment and electric dipole moment, the J-PARC muon g-2/EDM experiment is developing a 212 MeV muon linear accelerator [1]. So far, muons cooled to 25 MeV have been successfully accelerated to 90 keV [2].

In this experiment, since a low-emittance muon beam is required, high-precision position and profile monitors are necessary. In the early commissioning stage, fewer than 40 muons per pulse are expected, with additional background electrons from dark current, making measurements with commonly used types of monitors difficult. To address this, we have developed a novel beam profile monitor utilizing Cherenkov radiation.

This paper reports on the monitors for the 40 MeV and 212 MeV accelerator sections.

BEAM PROFILE MONITOR

Figure 1 shows a schematic of the muon linear accelerator. We are developing beam profile monitors at the entrance and exit of the Disk-Loaded Structure (DLS) section, which accelerates muons from 40 MeV to 212 MeV, corresponding to 70–94 % of the speed of light, with an accelerating gradient of 20 MV/m [3]. We are currently designing the monitors to be used at the entrance and exit. Unlike electron or proton linacs, the muon beam charge is extremely small; during early commissioning, the charge per pulse is only about 4 fC, several orders of magnitude lower than typical electron linacs. This requires high-precision diagnostics capable of operating with very low beam intensities.

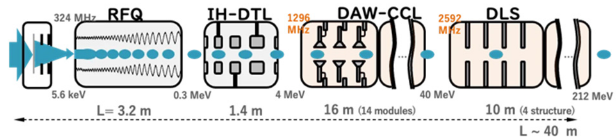

Figure 1: Layout of muon LINAC.

A major challenge is the dark current generated by field emission in the accelerating cavity, with electron energies up to ~14 MeV. Since muons and electrons carry the same charge, electrical measurements cannot distinguish them. When radiators with refractive indices of 1.46 and 1.08 are used in the monitors at 40 MeV and 212 MeV, respectively, the Cherenkov angles become 5.7° and 10.9°. The Cherenkov light emitted from relativistic-energy electrons is more than 4° larger than these angles. In the case of low-energy electrons, Cherenkov light is emitted at the same angle as that of muons; however, such electrons are strongly focused or defocused by the quadrupole magnets located after the accelerating cavity and thus cannot reach the detector. Therefore, only Cherenkov light originating from muons can be collected.

Figure 2 shows the monitor design. The optical system has astigmatism but no chromatic aberration because it uses only mirrors [4, 5]. Although the wavelength dependence of the radiator's refractive index must be taken into account, the entire wavelength range to which the detector is sensitive can be utilized. The Cherenkov light is guided through a vacuum window to an external CMOS sensor, which is shielded with lead and mounted on a motorized stage to allow focus adjustment.

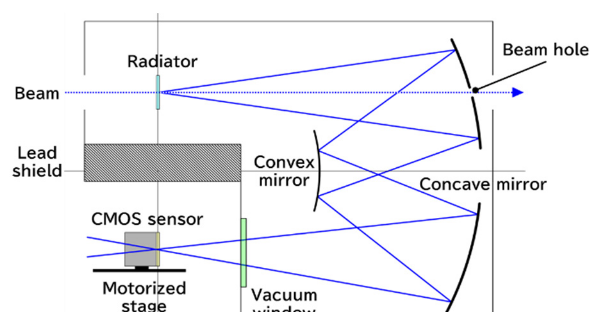

Figure 2: Layout of the beam profile monitor.

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OPTICAL SYSTEM RESOLUTION EVALUATION

In the Offner relay optical system [6], astigmatism arises when light rays emitted from an off-axis point source are focused onto different image planes along the tangential and sagittal directions of the spherical mirrors, causing image blurring. We evaluated the impact of this effect on the spatial resolution. First, we investigated the detector plane position and the corresponding image broadening. This evaluation allows for the quantitative determination of both the optimal sensor placement and the extent of image broadening in practical beam profile measurements.

In this study, ray-tracing simulations were performed using Zemax OpticStudio [7] to evaluate the effect of astigmatism in the Offner relay system as well as the optimum radiator thickness. The target design corresponds to a beam profile monitor for a 40 MeV muon beam, modeled under the conditions summarized in Table 1.

Table 1: Design of the Monitor for the 40 MeV Beam Section

Radiator thickness	5 mm, 10 mm, 15 mm, 20 mm
Radiator reflective index	1.46
Radius of curvature of spherical mirrors	Concave mirror: 560 mm Convex mirror: 280 mm

For the modeling of the Cherenkov light source, emission points were placed within the radiator at 0.5 mm intervals, and from each point, 360 rays were emitted conically at equal angular spacing to reproduce the spread of Cherenkov radiation. The transverse distribution of the muon beam was assumed to be a Gaussian with σ = 1 mm, and the number of particles was set to 1000.

With ray tracing, the light distribution measured at the detector was studied and the effect of astigmatism was evaluated. To assess the detector response, the CMOS sensor position was varied and the corresponding image size was investigated. If the detector is not placed at the optimal position, the measured image becomes elliptical. The image size as a function of the sensor position was fitted with quadratic functions in both the x and y-directions, and the average of the two focal positions was adopted as the optimal sensor placement.

To evaluate the relationship between the beam size and the measured spot size on the detector plane, simulations were carried out under several beam size conditions. Figure 3 shows the relationship between the beam size and the measured image size for a radiator thickness of 5 mm. The measured size σ_{meas} was fitted as a function of the beam size σ_{beam} using the following equation.

$$\sigma_{meas} = \sqrt{\sigma_{beam}^2 + \sigma_{resolution}^2},$$

where $\sigma_{resolution}$ represents the resolution of the detector.

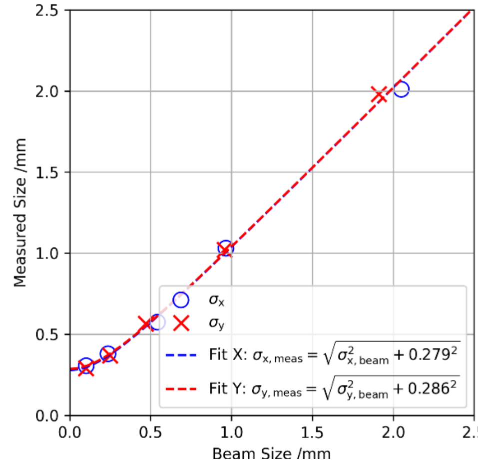

Figure 3: Measured image size on the optimal detector position as a function of beam size and its fitting, obtained with a radiator thickness of 5 mm.

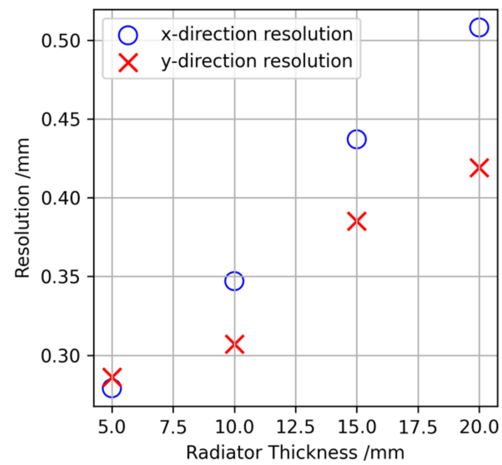

Figure 4: Resolution as a function of radiator thickness.

Table 2: The Number of Photons in the Detector Cell with the Highest Intensity

Radiator Thickness	Photon Count
5 mm	4.4
10 mm	8.9
15 mm	12.0
20 mm	14.7

The broadening due to the resolution is found to be smaller than the expected beam size of σ = 1 mm, indicating that the beam size can be measured with sufficient accuracy by subtracting this contribution. In practice, however, the actual spread will depend on factors such as mirror fabrication accuracy and alignment errors and therefore must be evaluated using the real system.

Simulation was performed to estimate the number of photons entering the detector. Figure 4 shows the resolution as a function of the radiator thickness. Although increasing the radiator thickness enhances the photon yield, it simultaneously degrades the spatial resolution; therefore, the minimum necessary thickness must be determined.

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For each radiator thickness, the number of photons entering the detector cell with the maximum intensity was evaluated, as summarized in Table 2. Even in the cell with the maximum brightness, the number of photons is small for 1000 muons. While the light yield is sufficient for beam position measurement, it is not sufficient for profile measurement. Therefore, the use of an image intensifier in the detector or a reconsideration of the conditions for profile measurement is also being examined.

RADIATION HARDNESS TEST OF AEROGEL

For the 212 MeV section, silica aerogel will be used as the radiator. Radiation damage could reduce transmission or alter the refractive index, affecting the accuracy of beam profile measurements. While γ-ray irradiation tests with ^{60}Co have shown no significant degradation [8], the effect of direct electron beam irradiation has not been studied. To ensure the long-term reliability of the aerogel, we plan irradiation tests using an electron beam. Changes in transmission will be measured with a spectrometer, and refractive index variations will be evaluated using the minimum deviation method [9, 10]. The experiment is scheduled at the Research Center for Electron Photon Science, Tohoku University, in late FY2025.

CONCLUSION

In this study, we developed a novel beam profile monitor for the J-PARC muon g−2/EDM experiment, aiming to measure the profile of a low-emittance, ultra-low-charge muon beam. The monitor utilizes Cherenkov radiation to discriminate muons from dark-current electrons, and an optical system was designed to selectively collect light originating from muons. An Offner relay configuration employing spherical mirrors was adopted, and a ray-tracing analysis was performed to evaluate the resolution, demonstrating sufficient capability for measuring the muon beam size.

To assess the radiation hardness of the silica aerogel used in the monitor, an irradiation test with an electron beam is planned, in which changes in refractive index and transmittance will be measured. As future work, we will evaluate the impact of alignment and positioning errors of the spherical mirrors and determine the required tolerances, study the effect of beam incident angle, and proceed with the fabrication of a prototype and optical testing.

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