

# DEVELOPMENT OF A NEW ULTRASLOW MUON BEAM DIAGNOSTIC SYSTEM FOR THE J-PARC MUON $g - 2$ / EDM EXPERIMENT

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## Abstract

Realization of a low-emittance muon beam requires injection of a phase-space-matched keV-scale muon (ultraslow muon) beam into an accelerator, since beam mismatch leads to emittance growth and reduced acceleration efficiency. In the J-PARC muon acceleration scheme, both invasive and conventional non-destructive diagnostics of such a beam are challenging because of its low energy and low intensity. Here we develop an ultraslow muon diagnostic system compatible with the accelerator under construction at J-PARC. The system is designed to evaluate beam conditions so that the beam can be precisely tuned for acceleration. Commissioning with ultraslow muon sources demonstrates the system's capability as a practical online diagnostic system for beam matching.

## INTRODUCTION

Development of a low-emittance muon beam is an important step toward next-generation muon science. Such a beam enables high-precision measurements of fundamental physics parameters, such as the muon magnetic dipole moment, and the search for the electric dipole moment [1]. It is also expected to play key roles in future applications including muon microscopy for probing internal structures of materials [2] and muon colliders for searches beyond the Standard Model [3]. Realization of these studies requires the stable production of a low-emittance muon beam. Conventional high-intensity muon beams are predominantly produced from pion decay in proton-irradiated targets. Such a muon beam is a tertiary beam and has a large phase space volume ( $\mathcal{O}(10^3) \pi \text{ mm} \cdot \text{mrad}$ ), which leads to poor matching to the acceptance of the accelerator ( $\mathcal{O}(1) \pi \text{ mm} \cdot \text{mrad}$ ) and consequently low acceleration efficiency. One promising approach is the acceleration of ultraslow muons produced via laser ionization of muoniums [4, 5]. In this scheme, surface muons stop in a silica aerogel target [6], form thermalized muonium atoms, and are subsequently ionized and accelerated toward a radio-frequency quadrupole (RFQ). The intensity of the ultraslow muon beam is on the order of fC.

Efficient RF acceleration requires accurate matching of the beam parameters to the RFQ acceptance. Accurate determination of the beam emittance and Twiss parameters at the RFQ entrance is therefore essential for beam matching. However, conventional diagnostic techniques [7] are difficult to apply because the beam is both low-energy and

low-intensity, while background particles from the upstream beamline further complicate signal identification.

In this work, we develop a diagnostic system to accurately evaluate the parameters of the low-energy and low-intensity ultraslow muon beam while separating the signal from the background and maintaining compatibility with accelerator operation. The system was installed between the muon source and the RFQ and is designed for flexible switching between acceleration and diagnostic modes. Its performance is then demonstrated through beam-based measurements. The experiments were carried out at Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC).

## DIAGNOSTIC SYSTEM DESIGN

The requirements of the diagnostic system are determined by the limited available space and the beam-matching conditions at the RFQ. To limit emittance growth in the RFQ to within 10%, accurate beam-parameter measurements are required. The main requirements for the diagnostic system are compactness, flexible mode switching, background suppression, and measurement of beam parameters with an accuracy of approximately 10%.

Figure 1 shows the schematic of the beamline including the diagnostic system. The upstream section consists of components for muon production, beam transport, and beam steering toward the RFQ. Because of its small momentum, the ultraslow muon beam is highly sensitive to ambient magnetic fields. To maintain the beam trajectory, the ambient magnetic field around the target is monitored using field probes and compensated using cancellation coils. Remaining beam shift is corrected using electrostatic deflectors. Downstream of the electrostatic deflectors, an electrostatic mirror (EM) [8] is used to vertically deflect the beam toward the diagnostic section. The EM, used for energy selection, can be retracted from the beam path by a retraction mechanism so that the beam passes to the downstream accelerator. The EM consists of a positively biased flat backplate and a grounded mesh electrode facing each other, separated by 20 mm and tilted by  $45^\circ$  with respect to the beam axis. A bias voltage of 5.7 kV, corresponding to the extraction energy of the muon beam, is applied to the backplate. A dipole magnet (bending magnet, BM) located downstream and used for momentum selection further deflects the beam by  $90^\circ$ . The magnet has a bending radius of 150 mm, is air-cooled, and operates at a central magnetic field of  $2.63 \times 10^{-2} \text{ T}$ . The combination of EM and BM suppress background parti-

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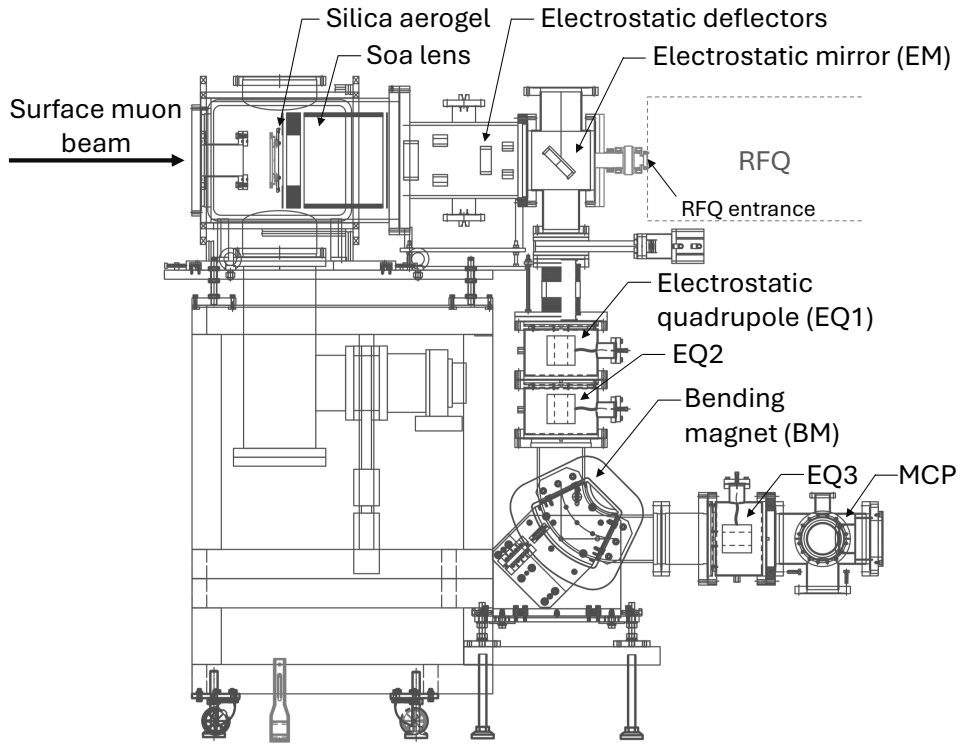


Figure 1: Side view of the beamline including the diagnostic system. In the upstream section, surface muons stop in the silica aerogel target and form muonium atoms, which are subsequently ionized by laser irradiation to produce ultraslow muons. Generated muons are accelerated to 5.7 keV and focused by the Soa lens, and transported toward the RFQ through the electrostatic deflectors. The diagnostic system, installed downstream of the deflectors, consists of EM, BM, EQ1–EQ3, and MCP. The ultraslow muons are transported through EM, BM, and finally detected by the MCP. EQ1 and EQ2 provide beam focusing, and EQ3 is used for the Q-scan. The total pass length from the silica aerogel to the MCP is 2.5 m.

cles before they reach a micro-channel plate (MCP) located at the end of the system. In addition, there are three electrostatic quadrupoles. Two of them (EQ1 and EQ2) are installed between EM and BM and provide beam focusing in combination with the edge focusing of BM. The last one (EQ3) sits just before the MCP to perform a quadrupole scan (Q-scan) [9] for beam parameter measurement. The beam envelope throughout the system is shown in Fig. 2.

Two types of MCP are used to detect ultraslow muons, depending on the parameters to be measured. For the measurement of the beam intensity and time structure, a single-anode MCP (SA-MCP; Hamamatsu F9892-21) is used which has an effective diameter of 42 mm and an open-aperture ratio of 60 % [10]. The output waveform is sampled by a digitizer (CAEN, V1751) with a sampling rate of 1 GS/s. For the transverse profile, a MCP coupled with a phosphor screen (BPM-MCP; Hamamatsu F2225-21P-Y003) [11] is used. The effective detection area is 40 mm in diameter. The image of the scintillation light from the phosphor screen (P47) is captured by a CCD camera (PCO pco.1600) with a timing gate set to 500 ns.

## MEASUREMENTS

The diagnostic system was developed for the MLF (H2 area) where an ultraslow muon source described in Ref. [1]

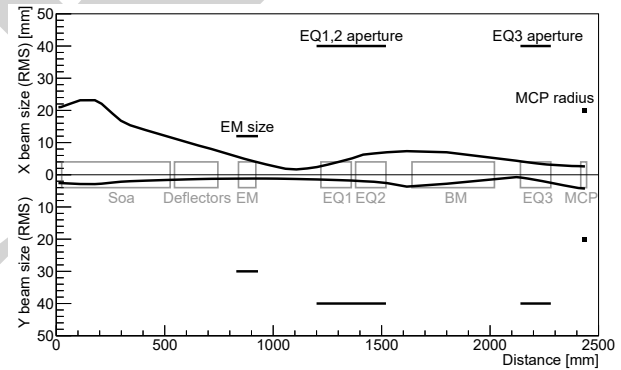


Figure 2: Beam envelope as a function of the distance from the silica aerogel. The curves in the upper and lower panels represent the horizontal (X) and vertical (Y) RMS beam sizes, respectively. The horizontal lines indicate the aperture sizes of the beamline components (the EQs and the MCP). The half-widths of the BM duct (37 mm in x and 59 mm in y) are not shown.

is being commissioned. Since stable ultraslow muon beam operation in the H2 area was not yet available at the time of installation, only signal identification measurements were carried out there. A feasibility check of the Q-scan method was subsequently performed in the other experimental area (S2 area), where ultraslow muons are stably produced using

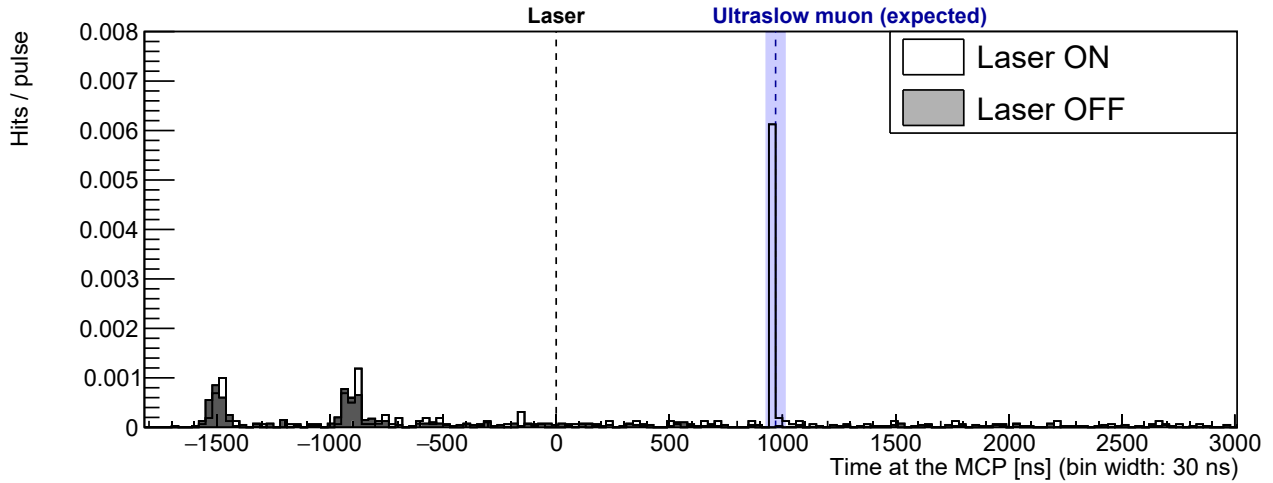


Figure 3: Time distributions of events at the MCP measured with (open) and without (fill) the ionization laser. The time origin ( $t = 0$  ns) is defined as the time of laser irradiation. Peaks observed around  $-1500$  ns and  $-900$  ns under both laser-on and laser-off conditions are attributed to signals originating from positrons produced upstream of the beamline. A clear peak is observed around  $970$  ns under the laser-on condition, corresponding to ultraslow muons produced by laser ionization and transported to the MCP. No significant signal is observed in the same time region without laser.

the same laser-ionization scheme as reported in Ref. [5]. These measurements were conducted during dedicated beam time from November to December 2025.

### Identification of Muon

Figure 3 shows the time distributions of events at the MCP measured in the H2 area with and without the ionization laser. The time origin ( $t = 0$  ns) is defined as the time of laser irradiation. Under the laser-on condition, a clear peak is observed at  $970$  ns, which is consistent with the time of flight of ultraslow muons expected from the simulation. In contrast, no statistically significant events are observed in the same time region under the laser-off condition. These results confirm that the delayed hits around  $970$  ns originate from ultraslow muons produced by the laser ionization of muonium. This result constitutes the first observation of ultraslow muons in the H2 area.

### Transverse Beam Emittance

The beam emittance in both horizontal and vertical directions is measured from the variation of the RMS beam size under different quadrupole field strengths using the Q-scan method in the S2 area. The beam size was measured with the BPM-MCP while varying the EQ3 voltage. The observed beam size squared is expected to show a parabolic dependence on the quadrupole strength, reflecting the beam focusing behavior. The emittance at the EQ3 entrance is obtained by fitting the measured beam size using the Q-scan formalism [9]:

$$\sigma^2(V) = \beta \varepsilon m_{11}^2(V) - 2\alpha \varepsilon m_{11}(V)m_{12}(V) + \frac{1 + \alpha^2}{\beta} \varepsilon m_{12}^2(V), \quad (1)$$

where  $V$  is the EQ3 voltage, and  $m_{11}$  and  $m_{12}$  are the elements of the transfer matrix. The analysis of the Q-scan data is currently ongoing.

## SUMMARY

A compact diagnostic system for ultraslow muon beams before RF acceleration was developed. The diagnostic system is designed to measure beam parameters at the RFQ entrance with sufficient precision. The measurements confirmed the first observation of ultraslow muons transported through the diagnostic system. The feasibility of the Q-scan method for transverse beam emittance measurement is currently under investigation, with data analysis ongoing. This system enables evaluation of beam parameters for low-energy and low-intensity particle beams and is essential for the realization of low-emittance muon beams.

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