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Development of a microchannel plate based beam profile monitor for a re-accelerated muon beam

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A B S T R A C T

A beam profile monitor (BPM) based on a microchannel plate has been developed for muon beams with low transverse momentum for the measurement of the muon anomalous magnetic moment and electric dipole moment at high precision, with capability of diagnosing muon beams of kinetic energy range from a few keV to 4 MeV. The performance of the BPM has been evaluated using a surface muon beam at J-PARC and additionally with an ultraviolet (UV) light source. It has been confirmed that the BPM has a dynamic range from a few to 10^4 muons per bunch without saturation. The spatial resolution of the BPM has been estimated to be less than 0.30 mm. The positron background from muon decays is an obstacle in muon beam profile monitoring and a partial discrimination of the positrons has been achieved under discrete particle conditions.

1. Introduction

The J-PARC muon $g-2$/EDM experiment [1] aims to measure the muon anomalous magnetic moment ($a_\mu = (g_\mu - 2)/2$) and the muon electric dipole moment (EDM) with high precision. A new beam line for muons (H-line) [2] is under development. The experiment requires a muon beam with small transverse emittance that is obtained by re-accelerating ultraslow muons. The ultraslow muons are produced from ionization of muonium (μ^+e^-) at thermal energy with lasers. Muonium is produced by stopping a surface muon beam in a muonium production target [3]. This muon beam with low transverse momentum will be re-accelerated to the momentum value of 300 MeV/c [4] while minimizing the increase of the transverse momentum ($\sigma_{p_T}/p = 10^{-5}$). The accelerated muon beam is injected to the storage area under 3 T magnetic field without electric focusing [5]. The experiment measures $g_\mu - 2$ with a precision of 0.1 ppm and the EDM with a sensitivity to $10^{-21}\ e \cdot$cm. Proper beam diagnostics are required for the development of this new muon beam.

In contrast to other surface muon monitors [6,7], our BPM is designed to measure a beam profile and relative intensity for each bunch simultaneously from low intensity (a few muons per bunch) to high intensity in the kinetic energy range from a few keV to 4 MeV. A BPM based on a Micro-Channel Plate (MCP) has been developed to obtain necessary gain and efficiency to measure a low intensity beam. There have been several experiments that have used detectors based on an MCP assembly to work with beams of muons, neutrons, ions, atoms and positronium [8–10]. Unlike other beams, muons are stopped in the MCP due to a short penetration depth and decay to positrons plus muon antineutrinos and electron neutrinos by the weak interaction. These positrons give signals in the BPM via penetration of the MCP channels.

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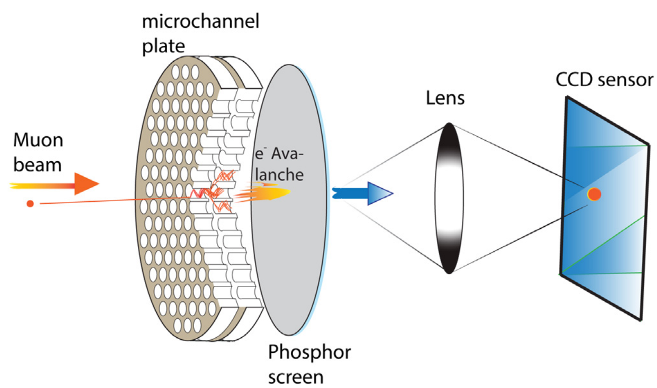

Fig. 1. A schematic view of the MCP based BPM.

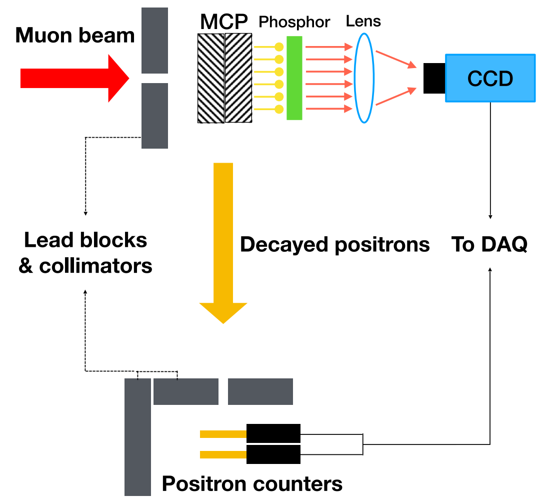

Fig. 2. Setup for the test with muon beam at the J-PARC MLF D-line D2 area.

Understanding and subtracting this positron background from the muon signal is one of the challenges in measuring a precise beam profile.

In this paper, we present the design and results of tests using the surface muon beam and the UV light source. The responses of muon and positron signals and the signal linearity were measured by the surface muon beam. The spatial resolution was measured by a UV light with a semicircular hole collimator.

2. BPM design and specification

Our BPM is designed to characterize a muon beam with sub-millimeter resolution for a ~10 mm beam spot size for the kinetic energy range from a few keV to 4 MeV corresponding to the low β section of the muon LINAC [4]. The BPM aims to measure a muon intensity from a few muons to 10^5 muons per bunch at a repetition rate of 25 Hz.

As shown in Fig. 1, the BPM consists of two stages of MCP, one stage of a phosphor screen and a charge-coupled device (CCD) camera. High efficiency for keV order atomic and ion beams has been observed in several experiments [11,12]. Similar high efficiency for a low energy muon beam is expected.

The MCP assembly (Hamamatsu F2225-21P) has two stages of chevron type MCPs with an effective area corresponding to a diameter of ⌀40 mm and gain of 10^6–10^7 plus a phosphor screen (P47). The light output from the phosphor screen is transmitted through a glass viewport (7056 borosilicate) and then captured by the cooled CCD camera (PCO pco.1600: 800 × 600 pixels with combined 2 × 2 binning mode) with lens (Zeiss Distagon 2/28 ZF.2). In order to block the electron background, negative potential (−1.9 kV) is applied in the MCP front surface. The MCP back surface is connected to a ground after an electric circuit to read out the electric signal of the MCP. Positive potential (3.9 kV) is applied to the phosphor screen.

The exposure time of the CCD camera is set to 0.5 μs to reject positrons from the muon decay (τ = 2.2 μs [13]). The P47 phosphor material Y_2SiO_5:Ce is chosen to have a short decay time ($\tau_{10\%}$ = 0.11 μs) compared to the exposure time to enable this discrimination method.

The MCP assembly is installed in the middle of a cylindrical vacuum chamber constructed from stainless steel. The MCP assembly and the CCD camera are aligned in the cylindrical axis. The vacuum chamber has a thin mylar film (0.1 mm) window with ⌀100 mm in a flange in front of the MCP assembly for beam transmission. Another mylar film window is installed in a side port for positron transmission. There is a viewport in a flange behind the MCP assembly.

3. Experiment with muon beam

3.1. Experimental setup

A schematic view of the experimental setup for the surface muon beam test is shown in Fig. 2. The J-PARC muon facility provides surface muon (μ^+) beam in single pulse mode to the Material and Life Science Experimental Facility (MLF) D-line D2 area with 100 ns beam width, 4 MeV kinetic energy, 25 Hz repetition rate, and the intensity of a few 10^6 $\mu+$/s [7,14]. The beam intensity was adjusted by slits in the beamline. The beam size and intensity were further adjusted by installing one of a set of lead collimators with ⌀10 mm, ⌀20 mm or ⌀40 mm hole between the exit window of the beam line and the BPM vacuum chamber. The MCP assembly was installed inside the BPM vacuum chamber which was separated from the beam line as an independent vacuum system.

The number of muons on the BPM was measured from decay positrons. A fraction of the decay positrons from muons stopped in the MCP volume go through the mylar film in the side port of the BPM chamber and give signals to the positron counter. The positron counter consists of two plastic scintillators with corresponding light guides and PMTs. The positron counter was shielded by lead blocks to suppress decay positrons from directions other than from the MCP. A lead collimator with a ⌀30 mm hole was used to provide a direct view of the MCP from the positron counter.

3.2. Data taking

Two dimensional pictures were taken by the CCD camera with 500 ns exposure time. The arrival time of the muon beam was measured by the electronic signal of the MCP. This timing information was used to set the proper timing for triggering the CCD exposure. The exposure at the arrival time of the muon beam (t_{delay} = 0 μs) was set by matching the center of exposure time window with the measured arrival time. The waveform data for the positron counter was taken for a 10 μs period in coincidence with the muon beam pulse.

Data with a few muons per pulse were taken to understand the properties of a single muon signal. Data with higher intensities were then taken by changing the sizes of the slit in the beam line and the collimator. Another set of data was taken with different trigger timing for the CCD camera to understand positron signals in the BPM. Typical CCD images taken at different intensities are displayed in Fig. 3. A raw picture (Fig. 3a) and the accumulation of 1000 pictures in a two dimensional histogram (Fig. 3b) were taken with the high intensity muon beam. Low intensity pictures are shown for camera exposure at the beam arrival (Fig. 3c) and for delayed camera exposure from the beam arrival by 2 μs (Fig. 3d).