Development of the CsI(Tl) Muon Beam Profile Monitor for the Muon $g-2$/EDM Experiment at J-PARC

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Abstract. In this work suggest a transverse muon beam profile monitor based on a thin CsI(Tl) screen with optical readout to measure an upcoming surface muon beam to the silica aerogel target of the muon $g-2$/EDM experiment at J-PARC. Description of main requirements to the monitor are given. The measurements of luminophore foil parameters with PMT and camera were done as well as the test of the monitor prototype with a surface muon beam at D2 area in J-PARC MLF.

1 Introduction

The muon $g-2$/EDM experiment E34 at J-PARC [1] aims to measure the muon's anomalous magnetic moment and electric dipole moment with a precision of 0.5 ppm and $10^{-21}\ e \cdot \mathrm{cm}$, respectively, to investigate the more than 3 standard deviation discrepancy between the Standard Model prediction [2] and latest experimental measurement [3].

The accelerator performance play a key role in the experiment so it should be accompanied by a proper beam diagnostic systems to monitor beam quality. Within this arise the task of continuously monitoring the upcoming to the aerogel target surface muon beam. The beam repetition rate is 25 Hz, each bunch has two 100 ns long spills with 600 ns delay, the total beam intensity is $10^8\ \mu^+/\mathrm{s}$ with $(27.0 \pm 1.3)\ \mathrm{MeV}/c$ momentum, the horizontal and vertical RMS of the beam in the target plane are 31 and 14 mm, respectively.

Basing on beam parameters we suggest to use a transverse beam profile monitor (BPM) based on a thin CsI(Tl) foil with optical readout. Prototype development of a such monitor has bean performed and report in this paper.

2 Beam profile monitor

The CsI(Tl) films are produced in the Budker Institute of Nuclear Physicsusing the thermal deposition method, [4]. Currently the scintillator screens with the diameter of a sensitive area up to 120 mm can be produced. This limitation is caused by the scintillator layer uniformity requirements and basically originates from the vacuum vessel overall dimensions. The

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Mylar film (DuPont, 2.9 µm $= 1 \times 10^{-5}\,X_0$, where X_0 is a radiation length) is chosen as a substrate and attached to an Al ring with a 3 mm × 4 mm rectangle cross-section. We choose the thickness of CsI(Tl) layer in the range 3–5 µm $= (1.6\text{–}2.7) \times 10^{-4}\,X_0$ to lower material budget but still have an easy detectable signal. The scintillator volume is characterised by a fine-grain structure with size from 1 to several tens of µm which depends on the type of the used substrate and on the rate of CsI(Tl) deposition. The choice of the CsI(Tl) scintillator among others is determined by its high light yield, about 50 γ/keV, low melting temperature — 894.2 K, operation in vacuum as well as in room environment, light emission in a visible range, and good radiation hardness.

The luminophore supposed to be placed on beam axis. Scintillator material will be excited by the passing through particles and emit visible light, which should be collected and detected by a camera by taking images. Two options are considered direct observation of the luminophore or see its reflection in a mirror. The mirror made of 2.9 µm mylar foil with an aluminium coating is suggested. Due to its low material budget is also can be installed on beam axis.

The available cameras afford different data taking strategies from taking one picture per beam pulse, what gives a high signal to noise ratio due to low photon statistics, and accumulate data for some time up to hour, to increase the obtained profile quality.

3 Test setup with α-source and PMT

To measure basic properties of a scintillation screen the sample of 4.8 µm CsI(Tl) foil with a 35 mm diameter of an active area was used. Measurements were done with irradiation of the foil by α-particles from ^{239}Pu source. To detect light the Hamamatsu R1847S PMT was used. It has a borisilicate glass window with a bi-alkali photocathode what gives a $\eta = 11\,\%$ quantum efficiency to the CsI(Tl) emission spectrum.

First of all we had measured the light yield of the foil. It corresponds to 2200 ph. e./α, what corresponds to $51 \times 10^3\,\gamma/\alpha$ applying correction for a geometrical efficiency $\varepsilon_{\text{geom}} = 40\,\%$ and quantum efficiency η. We expect the average energy deposition of α-particles in the luminophore on the level of 0.87 MeV, adding to this correction for the quenching effect [5] $1 + kB = 1.41$ one obtains specific light yield $\mathscr{L} = 81\,\gamma$/keV.

The next measurement was devoted to investigation of effectiveness of placing a reflector behind the luminophore screen to increase the light collection efficiency. As a result observations of signal were performed in two configurations. In one behind the screen, close to it as 2 mm, was placed a black absorber, while in another configuration it was a white reflector. The output reveals the signal increase on 50 %. That gives an opportunity for a BPM design upgrade by placing a Teflon foil behind the luminophore screen.

4 Test setup with α-source and camera

Before making a measurements with a test muon beam, the test with a luminophore screen, camera and α-source ^{241}Am was done in order to validate BPM's dimensions and camera performance. For this measurement and the following beam test the CCD camera pco.1600 with Zeiss Distagon 2/28 ZF.2 lens was used. It can take pictures with resolution of 1600 × 1200 pixels, while the pixel size is $7.4 \times 7.4\,\mu\text{m}^2$, the camera has Peltier cooling, which leads only to the $0.01\,e^-/(\text{s pixel})$ dark current, the same time 10 MHz digitisation rate leads to $11\,e^-$/pixel read-out noise. The camera's exposure time can be varied in the range 0.5 µs–49 days.

Several series of test was done. We took pictures with different exposure time to check the linearity of the linearity of the system. Take pictures with different distance between the camera and foil and with constant distance, but different angles of shooting, with purpose to show the isotropy of luminophore light emission, which was under the question because of grain structure of a CsI(Tl) layer.

5 Beam test at D2 beamline at MLF J-PARC

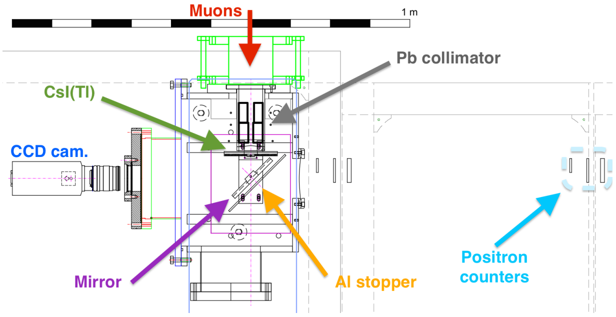

Figure 1. The beam test experimental setup scheme, top view.

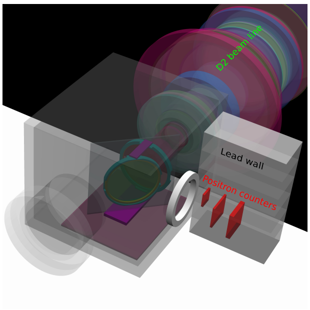

Figure 2. The view of the beam setup in Geant4.

The final test of our BPM was done with a help of the D2 line in Material and Life Science Facility at J-PARC. The D2 line provide a surface muon beam with the same time structure as the expected beam at the H-line, but has a lower intensity. During the beam time it was about $10^7\,\mu^+/\mathrm{s}$. The beam momentum can be varied, but the maximum intensity is achieved at $p = 27.4\,\mathrm{MeV}/c$, therefore it was used as a default configuration.

During the beam test we had used the CsI(Tl) foils of 3, 4.8 and 5 µm thickness and a CsI(Tl) monocrystal with dimensions $2 \times 2 \times 0.137\,\mathrm{cm}^3$. The crystal was used for tuning of apparatus and as a reference in data analysis.

The luminophore and, optionally, mirror was placed inside the vacuum chamber. Their observation was done through a Kovar glass window by the pco.1600 camera.

On other side through a mylar window the BPM was observed by a hodoscope assembled from three tail fish tail PMTs with plastic scintillators of different sizes about $6 \times 5 \times 0.5\,\mathrm{cm}^3$. This hodoscope are considered as a counter of muon decay positrons. The coincidence rate of positron counters was recorded.

The schematic top view of the experimental setup is presented on fig. 1.

We use a combination of two simulations to estimate the positron counter detection efficiency. G4beamline [6] based simulation is used to conduct particles through the D2 line taking into account the collimator configuration. This collimator was used to regulate the beam intensity. With help of Geant4 simulation [7] the positron registration rate is evaluated by using as primary particles output of G4beamline simulation. The detection efficiency of the coincidence of two positron counters is found to be $(4.4 \pm 0.3)\,\%$ for the detector configuration shown in fig. 2. What allows us to estimate the full beam intensity during the experiment to be $5 \times 10^6\,\mu^+/\mathrm{s}$.

The muon beam intensity was varied to compare foil light yield versus e^+ counter rate to find BPM linearity better than 5.5 % up to $10^5\,\mu^+/(\mathrm{pulse\,cm}^2)$ (see fig. 3).

During the beam time we had observed signal intensity about 0.01–0.04 ph. e./μ^+ with a 5 µm thick CsI(Tl) foil. Taking into account the difference in the quantum efficiency of the PMT and CCD sensor as well as acceptance (solid angle) of the camera we expect from the PMT measurements 0.01 ph. e./μ^+ in the CCD camera.

Pictures of the same foil was taking with the same beam condition but one time the CsI(Tl) side faced the camera other mylar side. The signal difference of two pictures applying position correction reveals 7 % signal raise in the observed light yield (see fig. 4). Two possible explanation can be employed: degradation of the CsI(Tl) open face due to contact with a humid environment, *i. e.* air, and smoothing of the refractive index gradient, which lead to ~20 % light leaving gain in the mylar case comparing to the CsI(Tl) case.

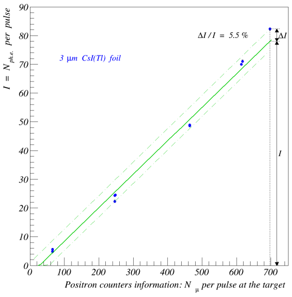

Figure 3. Linearity of the 3 μm foil.

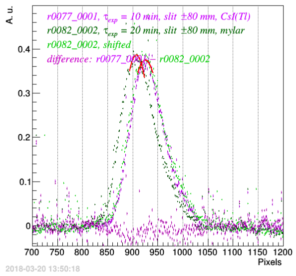

Figure 4. Comparison of horizontal beam projections, pictures taken from mylar and scintillator sides.

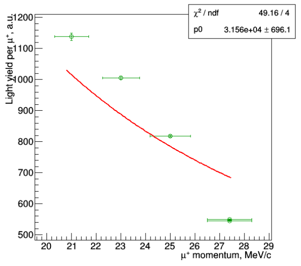

Figure 5. Dependence of signal intensity as function of beam momentum. Horizontal bars represent momentum spread.

Varying beam energy we had observed change in light yield per muon (see fig. 5). The overall tendency is described by Bethe equation.

6 Conclusions

The prototype transverse beam profile monitor based on a thin CsI(Tl) foil with optical readout has been developed and tested with pulsed surface muon beam at the D2-channel in MLF J-PARC. The beam test results show viability of such a monitor. Various BPM parameters has been measured. Now we are developing a CsI(Tl) BPM to use it with the H-line.

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