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

Georgiy Razuvaev[1,2,*], *Youngju* Cho[3], *Seonho* Choi[3], *Seungho* Han[3], *Evgeniy* Kozyrev[1,2], *Alexey* Petrozhitskiy[1], *Alexandr* Popov[1], *Tsutomu* Mibe[4], *Boris* Shwartz[1,2], and *Younghyun* Son[3]

[1]Budker Instute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[2]Novosibirsk State University, Novosibirsk, Russia
[3]Seoul National University, Seoul, South Korea
[4]KEK, Tsukuba, Ibaraki, Japan

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 selica 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} $e \cdot$ cm, respectively, to investigate the more than 3 standard deviation descripency between the Standard Model prediction [2] and latest experimental measurement [3].

The E34 experiment uses the positive surface muon beam stopped and cooled in an aerogel target, capturing their electrons and form a muoniums Mus (μ^+–e^- bound state) defuse downstream to be ionised in two steps by 122 nm- and 355 nm-lasers, then electrostaticly collected and re-accelerated up to 300 MeV/c by a linac. Accelerated muons are spiraly injected to the storage 3 T magnetic field on the 666 mm diameter stationary orbit, inside which the Si strip tracker of 40 vanes is placed.

The accelerator performance play a key role in the experiment so it should be accompied by a proper beam diagnostic systems to monitor beam quality. Within this arise the task of countiniously monitoring the upcoming to the aerogel target surface muon beam. The beam repetion rate is 25 Hz, each banch has two 100 ns long spills with 600 ns delay, the total beam intensity is 10^8 μ^+/s with (27.0 ± 1.3) 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 developent of a such monitor has bean performed and report in this paper with following contents: the second section introduce

*e-mail: g.p.razuvaev@inp.nsk.su

luminophore foil and BPM design, the next two sections narrate about investigation of BPM properties with PMT and camera setup, while the fifth section devoted to the beam test of the BPM prototype, finally leading one to conclusion.

2 Beam profile monitor

The CsI(Tl) films are produced in the Budker Institute of Nuclear Physics (Novosibirsk, Russia) using 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 Mylar film (DuPont, 2.9 μm = 1×10^{-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. The average velocity of CsI(Tl) deposition, layer thickness growing rate, is about 17 Å/s that determines the thickness precision. We choose the thickness of CsI(Tl) layer in the range 3–5 μm = 1.6×10^{-4}–2.7×10^{-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 temperatury — 894.2 K, operation in vacuum as well as in room enviroment, light emission in a visible range, and good radiation hardness. The radiation aging expressed in opacification of media and, consequently, absorption length decreasing. The later has not a large impact in the case of thin foils.

The luminophore supposed to be placed on beam axis. Scintillator material will be excited by the passing through particles and emmit 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 aluminum coating is suggested. Due to its low material budget is also can be installed on beam axis. The mirror allows one to easily observe the luminophore from a diseried angle and place a camera in a radiation protected area.

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 our, 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 with three spectral lines 5105.5, 5144.3 and 5156.95 keV kinetic energies. 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 400 ph. e./α, what corresponds to 2000 γ/α applaying correction for a geometrical efficiency $\varepsilon_{\mathrm{geom}} = 40\,\%$ and quantum efficiency η. We expect the average energy deposition of α-partciles 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 $\mathscr{L} = 20\,\gamma/\mathrm{keV}$.

The next measurement was devoted to investigation of effectivness 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 revials the signal increase on 50 %. That gives an oportunity 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 (main lines 5485.56, 5442.80 and 5388.23 keV) 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 was used. It can take pictures with resolution of 1600×1200 pixels, while the pixel size is 7.4 µm × 7.4 µm, the camera has Peltier cooling, which leads only to the 0.01 $e^-/(s\,px)$ dark current, the same time 10 MHz digitisation rate leads to 11 e^-/px read-out noise. The camera's exposure time can be varied in the range 0.4 µs–49 days. The camera is suited with a Zeiss Distagon 2/28 ZF.2 lens.

Several series of test was done. We took pictures with different exposure time to check the liniarity of the linearity of the system. Take pictures with different distance bteween 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 beacause of grain structure of a CsI(Tl) layer.

5 Beam test at D2 beamline at MLF J-PARC

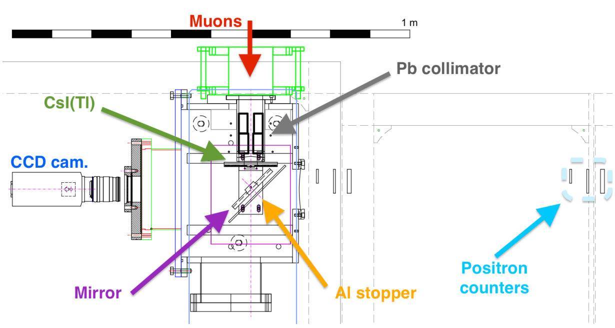

Figure 1. default

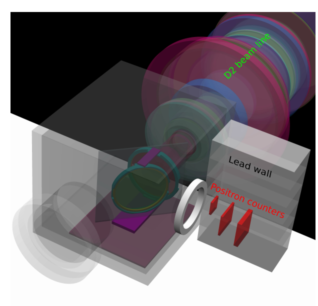

Figure 2. default

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 μ^+/s. The beam momentum can be varied, but the maximum intensity is achieved at $p = 27.4$ 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 20 mm × 20 mm × 1.37 mm. The crystal was used for tuning of apparatus and as a reference in data analysis. Along with the test a BPM configuration with a thin Al mirror was explored.

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

On other side through a mylar window the BPM was observed by a hodoscope assambled from three tail fish tail PMTs with plastic scintillators of different sizes:

3 cm × 3.5 cm × 0.5 cm, 6 cm × 6.5 cm × 0.5 cm and 6 cm × 5.5 cm × 1 cm. 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 experimetal 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 $(4.4 \pm 0.3)\,\%$. What allows us to estimate the full beam intensity during the experiment to be $5 \times 10^6\,\mu^+/\mathrm{s}$.

Varying beam collimator opening the muon beam intensity was being changed. Comparing light yield of different foils versus slit size and light yield versus e^+ counter rate can conclude that linearity of different foils is better than 5.5 % up to $10^5\,\mu^+/(\mathrm{pulse\,cm}^2)$.

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. In the PMT measurements of luminophore light yield 400 ph. e./α was observed. 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 evaluate 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. 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.

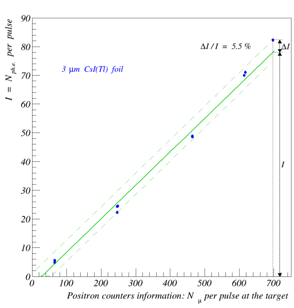

Figure 3. default

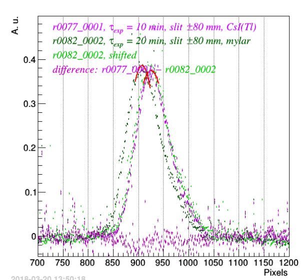

Figure 4. default

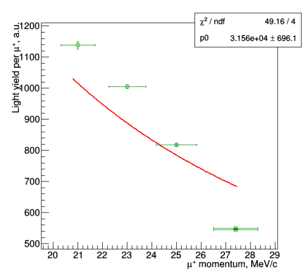

Figure 5. default

Varying beam energy we had observed change in light yield per muon. The overall tendency is described by Bethe equation. the horizontal bars represent beam RMS extracted from G4beamline simulation.

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.

Acknowledgments

We thank the J-PARC personal for excellent machine operation. The MCP assembly and CCD camera procurement and beam test preparation are supported by the Korean National Research Foundation grant NRF-2017R1A2B3007018. Work on the monitor software is partially supported by the Russian Foundation for Basic Research grant RFBR 17-52-50064, work on the beam profile monitor spatial resolution measurement is partially supported by the Russian Science Foundation grant RNF 17-12-01036.

References

[1] M. Abe et al. (2019), `1901.03047`

[2] F. Jegerlehner, Acta Physica Polonica B **49**, 1157 (2018), `1804.07409`

[3] G.W. Bennett et al. (Muon g-2), Phys. Rev. **D73**, 072003 (2006), `hep-ex/0602035`

[4] E.A. Kozyrev, K.E. Kuper, A.G. Lemzyakov, A.V. Petrozhitskiy, A.S. Popov, *X-ray Tomography using Thin Scintillator Films*, in *CERN-BINP Workshop for Young Scientists in e^+e^- Colliders: CERN, Geneva, Switzerland, August 22–25, 2016* (2017), pp. 65–70

[5] Y. KOBA, H. IWAMOTO, K. KIYOHARA, T. NAGASAKI, G. WAKABAYASHI, Y. UOZUMI, N. MATSUFUJI, Progress in Nuclear Science and Technology **1**, 218 (2015)

[6] *G4beamline*, `http://g4beamline.muonsinc.com`

[7] J. Allison, K. Amako, J. Apostolakis, P. Arce, M. Asai, T. Aso, E. Bagli, A. Bagulya, S. Banerjee, G. Barrand et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **835**, 186 (2016)