Low Energy Muon Beam Diagnostics: Scintillating Fiber Profile Monitor

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Abstract

The MeV Test Area (MTA) houses the 400 MeV H^- Beam at the end of the Linac and a secondary beamline of muons and pions created from hitting a Tungsten target. The MTA is in the Irradiation Test Area (ITA), where experiments involve studying the effects of radiation on materials in the MTA beam. There is a need for a retractable detector to monitor the secondary beam's intensity and coarse profile. The SFPM was chosen when considering factors like ability to measure low rates and handle high intensities. The plan was to test different scintillating fibers & Silicon Photomultiplier (SiPM) models to figure out which combination gives the best signals, and gain familiarity with the detector assembly, operation, and data acquisition software before using with final detectors in beamline. The SiPM circuit has been tested with a LED pulser successfully. The immediate steps that follow will be to set the SiPM up on the monitor with three different types of optical fibers, use the Caen software to configure the best mode of data acquisition, and proceed with an offline source test using Strontium-90. Once the most efficient measurement method is clear, they will be ready for use in the beamline.

1.1 Introduction

The MeV Test Area (MTA) is a beam enclosure, beamline, and service building at Fermi National Accelerator Laboratory (Fermilab). It receives a 400 MeV beam from the Linear Accelerator (Linac). At the end of the MTA beamline is the Irradiation Test Area (ITA), which is a shielded experimental cave. Its experiments involve studying the effects of radiation on materials and components in the MTA beam. The secondary beamline was recently installed to create a beam that produces pions that decay into muons. This is done by directing the MTA H^- beam into a Tungsten target. The interactions produce pions, which can decay in-flight into muons, or decay while still in the Tungsten target, called surface muons. The end of the secondary beamline will be the home of the Muon Catalyzed Fusion (μCF) experiment. This is one main purpose for the low energy muon beam.

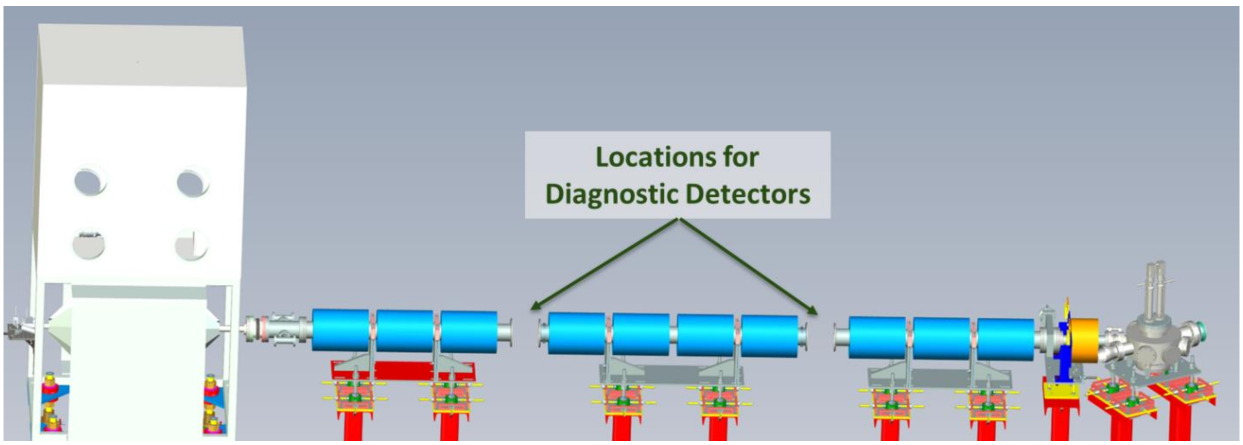

Fig. 1. — Graphical Representation of MTA Secondary Beamline Locations for Diagnostic Detectors

This secondary beam has a profile that needs to be monitored. The diagnostics requirements are measurements of the coarse profile and intensity of the beam. The muons in the beam are calculated to have a 100MeV/c momentum, resulting in approximately a 30 MeV kinetic energy for the beam. Based on these beam properties, it is apparent that the beam energy is relatively low. Low energy beams indicate that the detector material will cause scattering. This creates another requirement: the monitor needs to be retractable to prevent the beam from scattering [1]. The diagnostics should be able to measure low rates of particles – approximately 10^3 particles per pulse—yet be able to handle high intensities as well. The intensity will depend on factors such as the amount of primary beam, the target geometry, and the amount of secondary beam that can be captured and efficiently transported [1].

1.2 Profile Monitors

Christopher Izzo started this project at Fermilab in 2022. The type of detector chosen needs to meet the previous criteria. Some types of Fermilab beamline diagnostics include the segmented-wire ion chambers (SWICs) and proportional wire chambers (PWCs). The SWIC is a multiwire detector with a high voltage bias plane, wires at 45 degrees, and one plane each of horizontal and vertical signal wires. SWICs have a higher sensitivity, and can detect smaller amounts of beam than most multiwire detectors we use in Accelerator division. They accomplish this by flowing a mixture of Argon and CO_2 through the wires. These gas-filled detectors have been used to measure the profile and intensity of beams from 10^6 to 10^{12} particles per pulse since 1972 [2]. Therefore, the SWIC is not a candidate for the low energy muon beam. The PWC is another gas-filled chamber with the same mixture of the two gases as the SWIC except it has a much higher gain, an effect of the small diameter of the sensing wires and the negative polarity of the bias. The PWC measures intensities as low as 10^4 [3], so the intensities established by the MTA secondary beamline are still at the lower edge of its range.

A common choice for profile monitor detectors in muon beams is an X/Y array of scintillating fibers, housed by a metal frame, and using Silicon Photomultipliers (SiPMs) to readout the data from the fibers. Examples of these detectors are seen at labs worldwide for muon physics studies. Plastic scintillating fibers are made of a core and cladding that emit light when exposed to radiation. The core is usually made of polystyrene and allows photons to travel along it through total internal reflection. SiPMs are a method of amplifying the signal from the photons that enter them to readout the data. The signal is created by the movement of the electrons caused by the photons' entrance. This monitor, known as a scintillating fiber profile monitor (SFPM), has been used in the past to measure intensities lower than the threshold of the PWC. Additionally, SFPMs can be built with retractable housing, so the requisites are met with this detector, making it a logical choice for use in the muon beam.

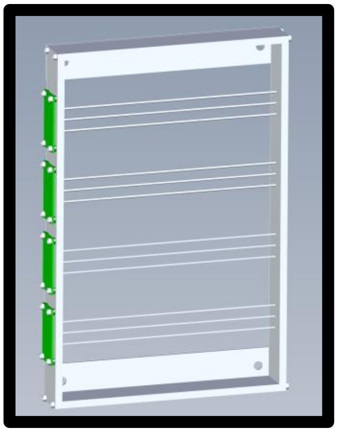

Fig. 2. – Graphical Design of SFPM for testing

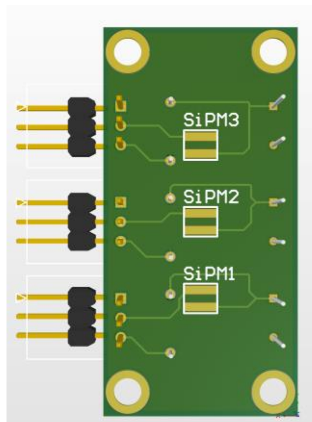

Fig. 3. – SiPM PCB Design side 1

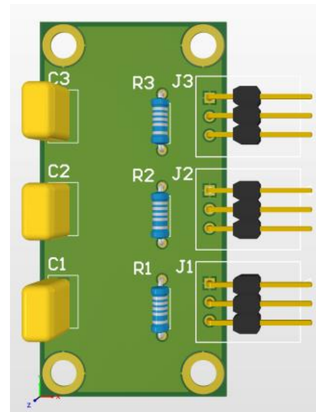

Fig. 4. – SiPM PCB Design side 2

A recent testing of Fiber Profile Monitors (FPM) at Fermilab determined that they are far more suitable for particle pulses of 10^4 or less. However, the same test proved that there were signal-to-noise ratio issues, as this ratio decreased when the beam intensity decreased [4]. The FPMs were eventually replaced by PWCs. However, a more recent attempt succeeded: the IBMS3 detector for the muon g-2 experiment. The plan was to model the MTA beamline detector after this by using the bayonet housing in a vacuum, but replacing the inner workings with a SFPM.

2.1 Progress

The SFPM designed for offline testing at Fermilab has an aluminum frame that is 31.6 cm long, 20.9 cm tall, and 2.9 cm wide. It has four sets of three holes where scintillating fibers will be inserted. The fibers will be bonded to the frames using an optical cement from Eljen Technology that is meant for use with plastic scintillators. The scintillating fibers are from Kuraray and Saint-Gobain. The choices for fibers are single-clad round or square and multi-clad round, with a 1 mm diameter. The SiPMs are from Hamamatsu Photonics. There are three types of them. Two of them are the same model, S13360, with different pixel pitch values of 50 μm and 25 μm. The third is a S14160 with a pixel pitch of 15 μm. Each has a 3.0 mm^2 photosensitive area. The SiPMs are placed on one side of the frame, where the components of the SiPM align with the fibers' ends. Components like connectors were soldered onto the circuit boards. Below is the design for one of the SiPM circuits of three that will go on the PCB shown in Figure 3.

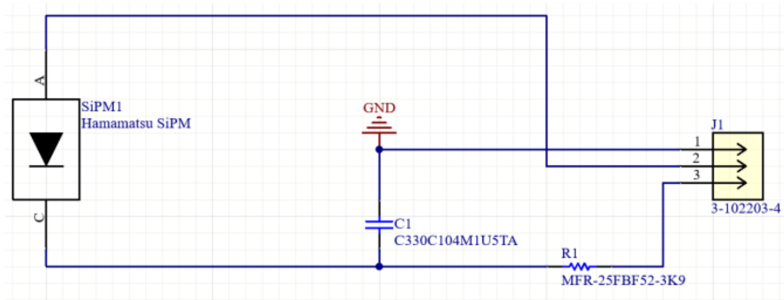

Fig. 5. – SiPM circuit design for one individual matrix

The fibers were polished on the end that faces the SiPM. This is to allow the photons to proceed through easily without interruption. A polishing tool called the FiberFin uses a diamond drill bit to accomplish this. The opposite side of the fiber was polished as well, and then it was given to a detector technician to insert a metal deposition to mirror the photons back toward the SiPM. There had been an assembly already. After two years in storage, the round, single-clad fibers had bent out of there straight shape, and some had broken off at the cemented locations. The fibers were removed using acetone, isopropyl alcohol, and a small pick tool. This process was difficult, but it was the recommended method by the manufacturer of the optical cement. The next step was to set up testing.

2.2 Testing

First, the test setup was with the Caen DT5202 front end readout system (FERS). It houses a Field Programmable Gate Array (FPGA) with 64 channels to acquire data through cable connections, and it has an ethernet or USB connection available to connect to a desktop. The Caen FERS has a compatible Graphical User Interface (GUI) software called Janus, where the user can acquire, analyze and plot data in different modes, like single particle counting, timing mode, and spectroscopy. The DT5202 has an internal test pulse that was used to gain familiarity with the software and the board. A function generator was used as an external source to pulse to the DT5202. The figures below are examples of testing the Citiroc chip in the FERS at relevant stages to see the output [5].

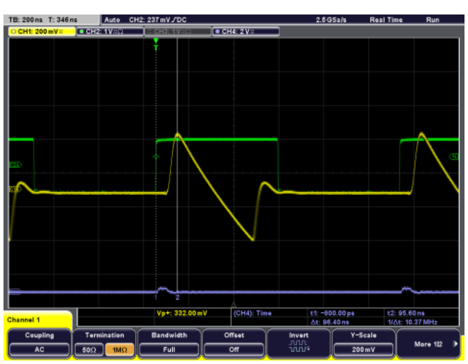

Fig. 6. – Pulse (green) and slow shaper HG signal (yellow)

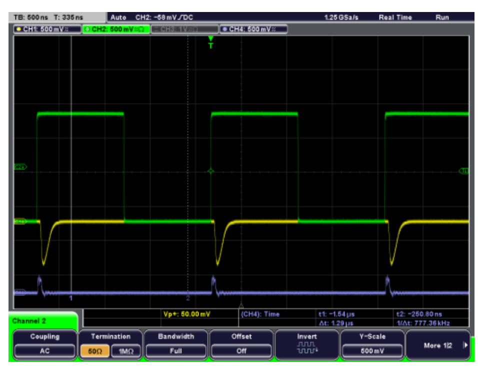

Fig. 7. – Pulse (green) and LG Preamplifier

The setup to test the SiPM matrix involved placing the circuit board in Figures 3 and 4 and a light pulsing device into a dark box so that no outside light pollutes the test, also known as dark current. The light pulser was connected to a function generator to send in pulse shaped waves with an amplitude of 3 volts at different frequencies. One of connectors on the SiPM was connected by cable to a channel of the FERS. The Janus software allows the user to set a bias voltage. This should be set based on the breakdown voltage of the SiPM. The bias voltage was set to 43 volts because 5 volts should be the amount remaining after subtracting the breakdown voltage.

Once the SiPM has access to voltage, the user can test for different parameters to optimize the readouts using the DT5202, such as Hold Delay and thresholds for the triggers. The hold delay is a value of nanoseconds, and the time discriminator (TD) coarse threshold was set to 395 after testing and plotting revealed an ideal value. The purpose of this scan is to find a threshold where dark current readout is minimized, which is performed with any LED pulse turned off. Hold delay allows the proper timing for selecting the value of amplitude to use from the SiPM signal. Each SiPM has its own values for threshold.

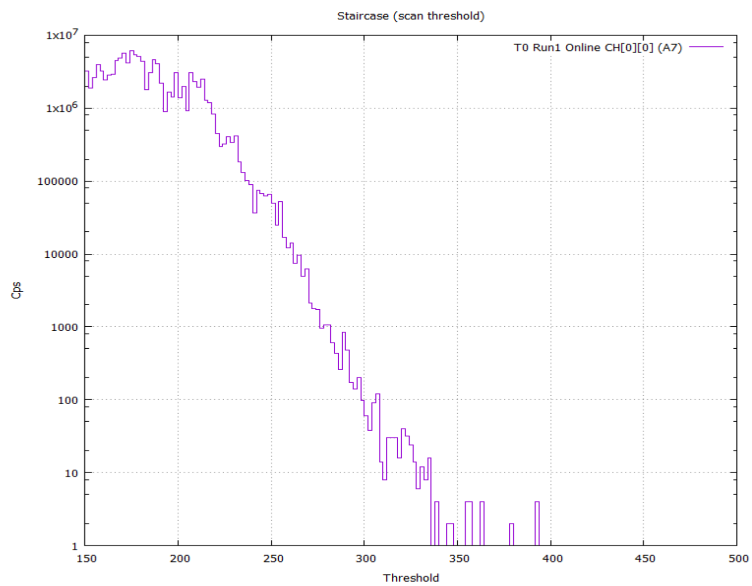

Fig. 8. – Staircase plot of a threshold scan showing counts per second vs. threshold value

The hold delay testing did not yield an adequate result, so a value recommended by the Caen user manual, the Hammamatsu SiPM data sheet, and an engineering physicist at Fermilab who specializes in electronics and SiPMs of 100 nanoseconds was used. Another recommendation was to make the High Gain (HG) shaping time as long as possible in order to allow time for the pulse to reach its maximum height before saving the value. The threshold value found during the testing was used during the setup with an LED pulser in a dark box. Once the discriminator output was seen on the oscilloscope, it was tuned to a frequency that gave a strong signal. To see the discriminator output, it was required to trigger properly. The single photon counting test was acquired in spectroscopy mode. The parameters configured on the Janus software were as follows:

High Voltage (HV) bias voltage = 53 V.

Max current = 10 mA.

Bunch trigger source = T-0 IN.

TD coarse threshold = 395.

HG gain = 50; Hold delay = 100 ns.

HG shaping time = 87.5 ns.

Pulse width = 5 ns.

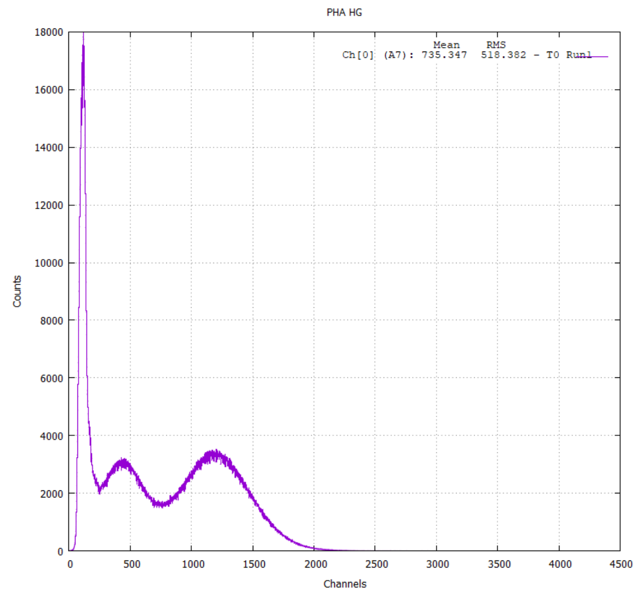

Fig. 9. – Pulse Height Amplitude (PHA) plot for the HG amplifier showing photon counts vs. channels triggered with visible photopeaks

Figure 9 shows a spectrum obtained for signals from the HG amplification chain. The three peaks from left to right were the result of a run when running the pulse function at varying voltages and a constant frequency of 25 kHz. The photopeaks were formed from 1-, 3-, and 5-volt amplitude pulses, respectively. If the run time increases, the respective height of the peaks will increase, as the 1-volt pulse was used for the largest portion of the run.

The results from the staircase plot indicate that the Caen FERS is capable of helping the user select parameters for any setup within a few minutes. The PHA plot shows that spectroscopy has the ability to measure photon counts at specific intensities, which could be used as a feasible mode for beam intensity measurement.

3 Future Work

The testing results indicate that the Caen FERS is an adequate component of the data acquisition required for its application to the MTA muon beam. There is a type of plot that would serve as an ideal representation of beam profile using multiple SiPM to cable connections called a 2D pulse height spectrum. Figure 10 shows an example of it. It is an ideal choice for an X-Y array of fibers, like the planned final design. This would look similar to the Inflection Beam Monitoring System (IBMS) for the Muon g-2 experiment at Fermilab.

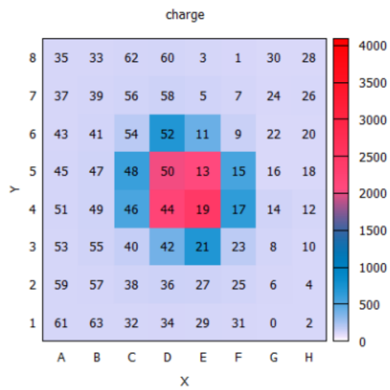

Fig. 10. – 2D pulse height spectrum without multiple channel readouts (2D Charge HG plot).

The materials to assemble the test monitors are all onsite at Fermilab. Over twenty-four round single clad fibers have been polished, yet the mirroring process has been delayed. The two other types of fibers will need to undergo the same process. The fibers were cut to a length of 21.5 cm to be slightly longer than the monitor frame and to anticipate more subtraction from the polishing tool. The assembly of the test monitors will require the use of optical cement, an adhesive specially designed for use with optical fibers, to fasten the fibers in place.

A lot of time was spent gaining familiarity with the Caen FERS hardware and software. Further results from testing are needed to determine the ideal combination of SiPM and fiber. The testing should continue with a light pulse. A successful test of the Hold Delay parameter should be a priority, and the failure to do so initially could indicate a flaw in the design or experiment setup. After confirmation of successful SiPM readouts, an offline radioactive source test should be used to generate data from testing to determine how it may perform in a muon beam. Consultation with other detector experts in the muon department at Fermilab could provide relevant information to expedite the testing phase.

This research helps the lab decide whether to use Caen FERS for further similar data acquisition missions. Learning about using an LED pulse source as a test for photomultiplier devices helps the lab because many experiments use different photomultiplier devices, like photomultiplier tubes (PMT). So much of this project involved help from employees at Fermilab. They were all willing and able to assist in some way with frame construction and test setup. This indicates that this project, as many are, is a group mission.

4 Reference

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