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Test beam studies of the light yield, time and coordinate resolutions of scintillator strips with WLS fibers and SiPM readout

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ABSTRACT

Prototype scintillator+WLS strips with SiPM readout for large muon detection systems were tested in the muon beam of the Fermilab Test Beam Facility. Light yield of up to 137 photoelectrons per muon per strip has been observed , as well as time resolution of 330 ps and position resolution along the strip of 5.4 cm.

1. Introduction

In our previous paper [1], several designs of scintillator strips for the muon system of a detector at a future collider experiment are described, the requirements on the time and position resolution outlined, and studies of prototype strips with cosmic rays are presented. Scintillator strips for a muon system are expected to be several meters long, ~1cm thick and several cm wide. They include wavelength-shifting (WLS) fibers to transport the light to both ends of the strip to be read out by a pair of silicon photomultipliers (SiPM). In this paper, studies of such scintillator strips in the muon beam at the Fermilab Test Beam Facility (FTBF) are presented using state-of-the-art low-noise SiPM and measurement settings designed to reach and measure the ultimate time and coordinate resolution with various strip-readout configurations.

The primary beam at FTBF consists of 120 GeV/c protons with particle intensity up to 300 kHz. For our tests this beam is used to create a secondary beam of pions. A secondary beam with particle momenta of 28 GeV/c is selected using dipole magnets. The muon beam is produced in flight by decay of pions, generating a broad distribution of muon momenta from 16 to 28 GeV/c. 183 m downstream from the momentum-selection dipole, a 3.2 m thick concrete absorber removes all beam particles except the muons. Muon fluxes achieved with this beam are about one hundred times higher than the cosmic radiation flux. This allows accumulation of statistics within a few minutes per data point. The 1 σ radius of the muon beam after the concrete wall is measured to be 5 cm, with a 1 σ angular spread of ~3° [2].

Intrinsic limits of the timing precision of SiPMs have been explored elsewhere using scintillators of several mm in size with direct SiPM readout [3,4]. Although different in size than the devices tested in our studies, these results demonstrate the excellent potential of the SiPM for time measurements. In this work, Hamamatsu S13360-3050CS SiPMs are used for light detection [5]. The low noise level of these SiPMs allows setting discriminator thresholds below the one-photoelectron signal amplitude level, thus effectively measuring the arrival time of the first photon.

The test setup used is described in Section 2, the tested strips are described in Section 3, results are discussed in Section 4 and conclusions are given in Section 5.

2. Setup

The measurement setup is shown in Fig. 1. S3 and S4 are Bicron® 404A scintillator strip counters with a 27 × 12 mm^2 profile and vacuum photomultiplier tube (PMT) readout. The length of S3 is 15 cm and the length of S4 is 40 cm. Both S3 and S4 are installed vertically, with the bottom end 5 cm below the beam center and the PMT connected to the bottom end. S5 is a scintillation counter with an area of 16 × 24 cm^2, thickness of 12 mm and a vacuum PMT readout. S3, S4 and S5 are aligned along the beam line. The distance between S3 and S4 is 10 cm and the distance between S4 and S5 is 95 cm.

The tested strip is mounted on a 4 m long aluminum bar, together with the readout boxes S1 and S2 containing the SiPMs and the

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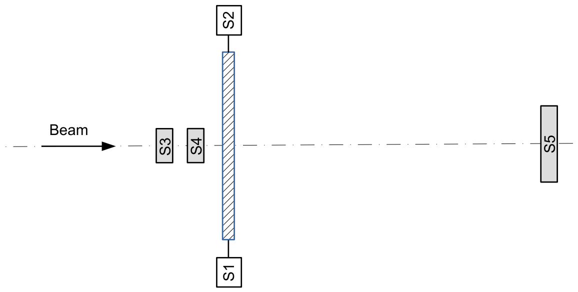

Fig. 1. Measurement setup seen from above (not to scale). The dash-dotted line represents the beamline.

preamplifiers. The aluminum bar is installed on an aluminum rail so that the bar can slide along the rail in the horizontal direction perpendicular to the beam. In this way different positions of muon impact, x, are scanned along the tested strips. The strip and the boxes are fixed to the bar so that the fibers connecting them do not move during the scans. To measure x during the scans an adhesive tape with distance marks at 1 cm pitch is affixed to the rail, and a reference position is marked on the sliding bar on which the tested strip is mounted. The reading $x = 0$ corresponds to the position of the bar in which the longitudinal center of the tested strip is located against the center of the trigger counters S3 and S4.

A CAMAC system with a LeCroy 2249A 12-input charge-sensitive ADC [6] and a LeCroy 2228A 8-input TDC [7] is used to digitize the amplitude and the arrival time of the signals.

The data collection is triggered by a coincidence between S3, S4 and S5. The signal amplitudes of the counters S3 and S4 are recorded for the offline selection of muons by restricting the analysis to events with at least 80% of the most probable muon energy deposit in both S3 and S4.

The signals from SiPM1 and SiPM2 are each split into two circuits using passive splitters. The signal in the time circuit is amplified using a Phillips Scientific model 776 fast $10\times$ amplifier [8] before the input of the constant-threshold discriminator. The signal in the amplitude circuit is attenuated using passive attenuators to match the dynamic range of the ADC.

For each tested strip configuration, a longitudinal scan of the irradiation position is performed in two gain modes: In the *low gain* mode, the bias voltages for the SiPMs are set to ~3 V above the breakdown voltage. This mode is characterized by a high uniformity of gain between pixels in the SiPM, allowing calibration of the single-pixel amplitudes from the amplitude spectrum of the SiPM (Fig. 2). The discriminator threshold for the SiPM time signals is set to $U_{thr} = 0.6\ U_{pix}$, where U_{pix} is the amplitude of the signal produced by a

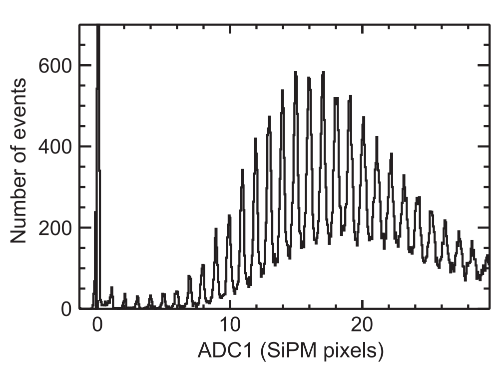

Fig. 2. ADC spectrum from a SiPM in the low gain mode mounted on one of the tested strip configurations from an overnight run with cosmic muons. Excellent pixel uniformity and low noise result in clear peak structure corresponding to integer numbers of firing pixels.

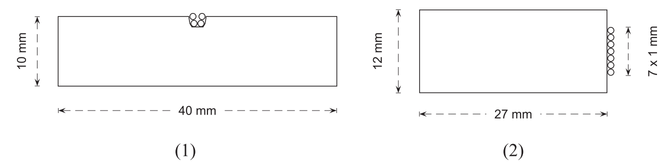

Fig. 3. Tested designs of the scintillator strips with WLS fibers: (1)MINOS strip with four Bicron WLS fibers, (2) Bicron strip with seven Bicron WLS fibers.

single SiPM pixel. In this way the recorded time corresponds to the arrival of the first photon.

In the *high gain* mode, the bias voltages are set at ~7 V above the SiPM breakdown voltage. In the high gain mode the photon detection efficiency is 40% higher than in the low gain mode and is close to saturation for this type of SiPM [5]. The increased photoelectron yield provides better time resolution. The crosstalk between pixels is also higher by several percent in the high gain mode. Because of the higher dark count rate of the SiPMs in the high gain mode, the discriminator threshold is set to $\sim 1.3\ U_{pix}$, effectively corresponding to the arrival of the second photon.

3. Scintillator strip designs

Two designs of the scintillator strip with WLS fibers are tested, corresponding to the best-performing designs from Ref. [1], and schematically presented in Fig. 3. The description of the studied strips, fibers and light insulation is the following.

Design (1) uses clear polystyrene scintillator strips with a $40 \times 10\ mm^2$ cross section with a central groove, co-extruded with a TiO_2 loaded surface layer such as used for the MINOS detector [9]. The inner surface of the groove is not covered with the reflective layer. Four Bicron® BCF-92 WLS fibers of 1.0 mm diameter [10] are inserted into the groove and covered with white Tyvek® sheet type 1056D [11,12]. The capacity of the groove to accommodate WLS fibers is thus fully exploited. The strip is then wrapped in several layers of black Tedlar® paper [11,12].

Design (2) uses clear Bicron® 404A fast scintillator strip with a $27 \times 12\ mm^2$ cross section [13]. Seven Bicron® BCF-92 WLS fibers of 1.0 mm diameter are attached to the narrow side of the strip using adhesive tape. In this design, the number of WLS fibers is limited by the sensitive surface of the used photodetectors. The strip is then wrapped with one layer of the Tyvek® sheet and several layers of black Tedlar® paper.

In both designs, the ends of the fibers extend 20 cm beyond the end of the strip and are bundled together. In the design (1), the four fibers are bundled in a square shape, and in the design (2) the seven fibers are bundled so that six fibers surround one in a tight hexagonal shape. Mechanical connectors are used to precisely position the end of the fiber bundle in front of the SiPM for efficient light collection. No optical glues or greases are used between the fibers and the scintillator strips or the SiPMs. The SiPMs have an active surface area of $3 \times 3\ mm^2$ and fully cover the fiber bundles.

The tested strips include two strips of design (1), one with the length of 1 m (strip A) and one with the length of 2 m (strip B), and one strip of design (2), with the length of 1 m (strip C).

4. Results

The analysis of all measurements is performed using the following off-line selection criteria:

- Presence of a signal is required in both SiPMs (TDC receives a stop signal before counting to end-of-scale)
- Energy deposit in each of the counters S3 and S4 is at least 80% of the most probable deposit for a muon.

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