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Test of scintillator bars coupled to Silicon Photomultipliers for a charged particle tracking device

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ABSTRACT

This work is the first step in the implementation of a tracking detector for instrumenting a light spectrometer to study O(1 GeV) ν_μ CC interactions. A spatial resolution of O(1 mm) is required for the precise determination of momentum and charge of muons produced in such interactions. A tracking system prototype composed of planes of scintillator bars coupled to Silicon Photomultipliers in analog mode readout has been developed. The devised system provides a spatial resolution of better than 2 mm in reconstructing muon tracks. Results obtained in laboratory tests and with cosmic ray muons are discussed.

1. Introduction

The main aim of the WA104-NESSiE project was the development of innovative experimental solutions to search for sterile neutrinos at ~1 eV mass scale [1,2]. Among the planned activities the construction of a light spectrometer seated in a magnetized air volume was foreseen. The whole design was optimised for the determination of the momentum and charge of muons in the 0.5–5 GeV/c range with a momentum resolution of 5% up to 3.5 GeV/c and a charge mis-identification <3% at 0.5 GeV/c. Monte Carlo (MC) simulations showed that a tracking device of low-density material providing a spatial resolution of ~1.5 mm would be required.

In this paper we report the results obtained with a small array of triangular scintillator bars with WaveLength Shifter (WLS) fibers and coupled to Silicon PhotoMultipliers (SiPM). Solid polystyrene scintillator bars are commonly employed in several experiments for particle physics [3–10]. In our tests we have used extruded bars produced at FNAL [11]. We show that the required spatial resolution in reconstructing the position of the crossing particles (cosmic ray muons) can be achieved determining the energy released in adjacent bars by the analog read out of SiPM signals.

SiPM features like single photon detection, reduced size, low power consumption, insensitivity to magnetic fields [12] make them a natural choice in designing a large tracking device to be placed inside a magnetized volume. Tests were performed in order to characterize the response of scintillator bars and SiPMs.

2. SiPM characterization

In our tests we used the MicroSL-10035 X13 SMD SiPM provided by the SenSL [13] manufacturer. This device has an active area of ~1×1 mm^2 with 504 microcells, and an overall fill factor of 64%. The breakdown voltage, as reported in the datasheet, is (27.5 ± 0.5) V and the overvoltage V_{bias} is allowed to range between 1 and 5 V.

In order to assess the performances of the selected SiPM and to characterize the working conditions for our tests, we determined the main sources of its noise and studied the effect of the temperature on its response and linearity.

2.1. Dark current

The main source of noise limiting the SiPM single photon resolution is its “dark current” rate, namely the rate of spurious current pulses produced in absence of light. The dark current pulse height distribution, measured at a working voltage V_{wk} of 29 V and at a temperature of ~26 °C, is shown in Fig. 1.

The dependence on the temperature of the single pixel dark current rate was investigated by keeping the SiPM in thermal contact with an aluminum bar cooled down by a Peltier cell. In the 18 – 28 °C range (typical of a lab environment) a variation of the dark current rate of ~5%/°C was estimated. In order to keep the dark current at low rates the value of V_{bias} was set to 1.5 V corresponding to V_{wk} ~29 V.

The rate of the optical crosstalk between pixels depends weakly on the temperature; variations of 15–16% were measured for tempera-

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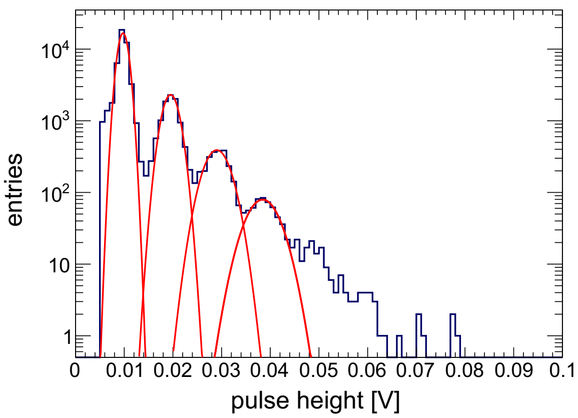

Fig. 1. Pulse height distribution of the dark current for the MicroSL-10035 SiPM. The total collection time was 25 ms at V_{bias}=1.5 V and T = 26 °C. The dark current rate, including contributions from other noise sources (i.e. cross talk and after pulses) is ~900 kHz, with a cross talk probability of about 15%. The Gaussian curves (red) are drawn to identify the first four peaks. The 5th and 6th peaks are also barely visible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tures ranging from 18 to 28 °C.

3. Front-end electronics

The front-end board dedicated to the amplification and SiPM readout was developed by the Bologna INFN electronics group. The amplification system is a two-stage transimpedance amplifier used to convert the SiPM current to an output voltage. Given the low input resistance of the transimpedance amplifier (using the OPA 656N amplifier with 500 MHz bandwidth), signal rise times of 20–30 ns are obtained. The amplifier output is split in two chains: an integration and shaping chain with a time constant of about 150 ns and an amplification chain with a gain of 10.

Each front-end board, used for the tests described in Section 5, handles 8 channels. The electronic noise fluctuation amounts to less than 10% of the single pixel signal amplitude.

4. The detector unit response

The design of the particle tracker is based on scintillator strips with a triangular cross-section with a height of (17.0 ± 0.5) mm and a base of (33.0 ± 0.5) mm [11]. The bars are 50 cm long, each with a (2.6 ± 0.2) mm diameter central hole to lodge the WLS fiber. The lateral surface of the scintillator strips is painted with white titanium dioxide paint (Eljen EJ-510 TiO_2).

The scintillation light is collected by 1.2 mm BCF-91A WLS fibers produced by Saint-Gobain Ltd. [14]. The fibers are glued to the strip along the hole with the RTV 615 optical glue and the ends are polished. The read-out is done only at one end of the bar; the other end is mirrored with reflecting tape to maximize the light collection.

The coupling between the WLS fiber and the SiPM is obtained by means of a plastic mask properly shaped to host the SiPM and tightly coupled to the sensor surface.

4.1. Tests with laser pulses

The SiPM response to the light hitting its surface is determined by the product of the photon detection efficiency (PDE) and the gain factor. For the SiPM under test the PDE, which is wavelength dependent, is about 15% at $\lambda \sim 500$ nm. At our working conditions, V_{wk}=29 V and T ~ 26 °C, the gain is ~6 × 10^6. The amplitude of a pixel signal is ~10 mV. The charge spectrum shown in Fig. 2 was obtained by injecting into the scintillator bar laser pulses produced by a Picosecond

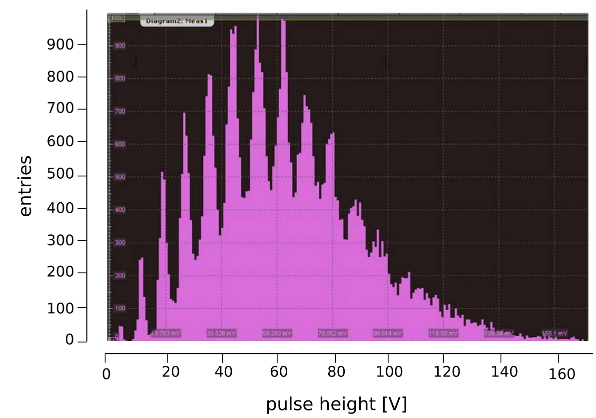

Fig. 2. Charge spectrum of a SiPM obtained by injecting laser pulses on the scintillator bar at a distance of ~6 mm from the WLS fiber. The signal amplitude peak corresponds to six fired pixels; the individual pixel value is ~10 mV.

Diode Laser (PiLas) [15]. The laser pulses were driven by a fiber to the front surface of the scintillator bar at a distance of 6 mm from the WLS fiber. The variation of the peak amplitude induced by the temperature amounts to 0.25 mV/°C.

In our tests we aimed at the detection of minimum ionizing particles (m.i.p.). The expected number of light photons produced by a m.i.p. in the scintillator strip is much smaller than the number of SiPM cells [6], therefore possible issues related to the dynamic range and linearity can be neglected.

Being the pulse height and the pulse area strictly proportional, we use indifferently mV or ADC counts to indicate the measured SiPM outputs.

All detector units were tested with laser pulses. The SiPM response was checked and the WLS-SiPM coupling investigated for possible source of signal loss. Bar intercalibration factors ranging from 5% to 10% were also determined.

5. Cosmic ray muon tracks

5.1. Detector layout

In order to determine the spatial resolution of a device composed of planes of triangular bars equipped with SiPMs in analog readout mode, a simple tracking system was set up. It consisted of two modules separated by ~12 cm, each composed by two faced planes of 4 scintillator bars (see Fig. 3). Each detector module was inserted in an aluminum box. In order to guarantee a good coupling between the sensor and the WLS fiber, SiPMs were plugged in a cap at one end of the aluminum box. The 8-channels front-end board was soldered to the external cap edge. In each module the triangular bars were tied together and the aluminum box was placed in a mechanical support structure.

The apparatus was tested with Cosmic Ray (CR) muons crossing the detector almost vertically along defined positions. For this purpose an external trigger system was added. The detector modules were located between two trigger stations separated by ~40 cm. Each trigger station was composed by 8 staggered scintillator rectangular bars (60×4×1 cm^3 each) equipped with WLS fibers, read out by SiPMs. Sensors provided by the AdvanSiD Co. (ASD-SiPM1S-M-100) [16] have been used. The arrangement of the rectangular bars was such that 6 different trigger configurations were possible. In each trigger 4 scintillators were over threshold (~60 mV) thus allowing the selection of muon tracks within windows 5 mm or 2.5 mm wide.

The aluminum boxes could be displaced horizontally with respect to the fixed rectangular bars with an accuracy of a fraction of mm. The overall uncertainty in the nominal up/down relative positions of the triangular bars was <1 mm.