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A multi-purposed detector with silicon photomultiplier readout of scintillating fibers

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ABSTRACT

Today, high position and timing resolutions can be simultaneously achieved using scintillating fibers coupled to silicon photomultipliers. In the framework of the MEGII experiment (MEG upgrade) which searches for the $\mu^+ \to e^+\gamma$ decay we are developing an active muon stopping target of 250 μm square scintillating fibers coupled to silicon photomultipliers. This tool should provide an unique way to continuously monitor the beam (detecting the stopped muons) at the highest muon beam intensities in the world, and to measure the muon decay vertex (detecting the outgoing positron). A similar technology will also be applicable to the Mu3e experiment which searches for the $\mu^+ \to e^+e^-e^+$ decay. In this experiment a timing hodoscope, which complements the silicon tracker, will be made by few layers of 250 μm square or round scintillating fibers, providing timing measurements with a resolution < 1 ns.

In this work we report the results obtained with the current prototypes showing that spatial resolutions at a level of 70 μm and timing resolutions of the order of 350 ps can be reached with a detection efficiency $\geq 90\%$.

1. Introduction

Scintillating fibers coupled to photosensors provide flexible, fast and high granularity detectors which are able to work in high rate environment [1]. The advent of Silicon PhotoMultipliers (SiPMs) has had a strong impact in the development of what we can call a "new age" of fiber based detectors. Improved detector performances (better spatial and timing resolutions) can be reached with respect to previous detectors, where PhotoMultipliers (PMs) were used, thanks namely to (1) the small photosensor size which allows to couple each single fiber to its own SiPM and (2) the reduced transit time spread of the photosensor itself. Furthermore the possibility of using SiPMs in magnetic fields strongly simplifies the implementation of such detectors used as tracker devices or to complement the latter, where usually a magnetic field is needed.

We are developing two detectors based on fibers coupled to SiPMs: a first one that should work simultaneously as a beam profile monitoring, counter device and a vertex decay detector, and a second one that provides timing information to complement a tracker.

A detector of the first type could find its application in the framework of the MEGII experiment (MEG upgrade) [2,3], which searches for the $\mu^+ \to e^+\gamma$ decay, as an Active muon stopping TARget (ATAR) of a single layer of 250 μm square scintillating fibers coupled to SiPMs [4–6]. This tool should provide a unique way to continuously monitor the beam at the highest continuous muon intensities in the world (detecting the stopped muons) and to measure the muon decay vertex (detecting the outgoing positron).

The muon rate counter at such a high beam intensities (up to 10^8 μ/s, where the sigma of the beam profile is ≈ 10 mm) requires a high granularity of the detector, provided by the usage of the smallest scintillating fiber available on the market. On the other hand a minimal amount of material is mandatory to minimize the positron multiple scattering and γ-background production. As a consequence the default minimal design features a single layer of 240 square fibers, 250 μm thick.

The main challenge lies in the detection of the positron (minimum ionizing particle) in such thin layers of scintillator material. The energy deposit is expected to be about 35 keV, equivalent only to few detected photoelectrons (phe). Extreme care in the design and construction of the detector is needed to successfully collect the few photons with maximum efficiency. The detector will work in a magnetic field (≈ 1 T), and in such conditions SiPMs exhibit the best photosensor performances. The intrinsic thermal background source

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due to the high SiPM dark current rate (current value $R_{DkC} \approx$ 100 KHz), which overlaps with the positron signal region, poses an extra challenge. This background is removed with the help of an external trigger, without requiring complex and non-allowed cooling systems (due to space constraints). Each fiber is read out by its own SiPM. Two configurations are under study: a so called “double readout”, where both ends of the fiber are coupled to the photosensors and the “single readout”, where only one end of it is coupled to the SiPM; the other end of the fiber features a reflector deposit to gain in light collection and detection efficiency w.r.t. the configuration in which no reflector is used.

A similar technology will also be applicable to the Mu3e experiment which searches for the $\mu^+ \to e^+ e^- e^+$ decay [7]. In this experiment, the tracker consists of High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) based on silicon devices in combination with a fiber hodoscope read out by SiPMs. The latter appears to be a valuable solution, providing a fast and low material timing detector, useful for track reconstruction. The expected high rate and the request to minimize the material budget suggest a hodoscope design made by few layers of 250 μm square or round scintillating fibers. A timing resolution less than 1 ns is needed for that purpose.

In this work we focus our attention on the basic elements (single fiber and fiber array, single- and double-readout) of more complex devices with a very large range of applications from astrophysics [8] to medical physics [9]. The challenge is to improve the performances of these detectors for which the total thickness of the scintillating fiber device is reduced to the minimum.

2. Experimental setup

Several target prototypes have been built (single fiber and fiber array, single- and double-readout) based on Saint Gobain multi-clad square fibers with a thickness of 250 and 500 μm. Different ways of fixing the fiber on the support without changing or reducing the optical transmission properties were tested. In all cases, fibers' ends were polished by planing them with a diamond cutting head. For the single readout scheme, a 100 nm thick layer of aluminum (Al) is deposited onto the free end of the fiber. For the array configuration, an Al film of 100 nm across the whole length of the fiber has been deposited to address the critical point of minimizing the optical cross-talk: a compulsory condition to reach a position resolution of $\sigma \approx 70$ μm with a single layer of fiber and, in the specific case of ATAR where muons and positrons are detected simultaneously, to avoid that a cross-talk signal induced by the high energy deposit of a muon event that mimics a positron event. The fibers were glued together to form an array using the Saint-Gobain BC600 optical cement.

The Hamamatsu S12571-100C SiPMs (active area $= 1 \times 1$ mm^2, pixel size $= 100$ μm^2, photon detection efficiency (PDE)=35%, gain$=2.8 \times 10^6$, for all the other parameters see [10]) are coupled to the 250 μm fibers while the Hamamatsu S12571-050C SiPMs (pixel size: 50 μm) are coupled to the 500 μm fibers.

The prototypes have been studied in the laboratory using a Sr90 source. An external trigger made of a BC400 plastic scintillator $18 \times 18 \times 23$ mm^3 coupled to a Hamamatsu PMT 5900U was used to select minimum ionizing particles (using an equivalent threshold of ≈ 1.5 MeV) and to reject the SiPM thermal noise, without requiring a cooling system.

Although SiPMs have extensive advantages with respect to the PMTs, they have low gain and therefore require an amplifier. A low-noise amplifier circuit (noise level < 10 mV peak-to-peak) was developed and optimized for low light collection, based on the Mini-Circuits MAR-6 gain block device [11].

The DRS evaluation board (based on the DRS4 chip) was used as data acquisition system [12]. The waveform signals were recorded with a digitization frequency of 5 GSample/s. A custom data analysis code was written and used to extract for each event the charge, integrating the waveform in a 20 ns time window, and the time, using the constant fraction method. The spectra shown in the following are not corrected for the SiPM pixel cross-talk and the after pulses.

3. Data analysis and results

In our previous works we have shown that we can distinguish between highly ionizing particle (such as stopping muons) and minimum ionizing particles [4–6]. There we already described the benefits due to the Al deposit for the purpose of the light reflection at the end of the fiber, for the single readout scheme. As a reminder we mention here that the light collection was measured to be a factor 1.5–1.8 more than in the case without Al deposit. A standalone MC simulation based on Geant4, including a custom SiPM response, was developed and validated with the data [13]. Here we focus our attention on the improvements achieved concerning the general performances of the prototypes, reporting our current best results in terms of light collection, detection efficiency, position and timing resolutions. In all the following sections the length of the fibers is ≈ 25 cm if not specified. The fibers are irradiated with electrons from Sr90 source selecting only the hard part of the spectrum ($E > 1.5$ MeV).

3.1. *Prototypes based on* 250 μm *thick fiber*

Fig. 1 shows a typical charge spectrum collected on one end of a single fiber coupled to its own SiPM, when electrons were fired at approximately half the total fiber length. The collected charge is converted into the equivalent number of phe. A mean of $N_{phe} \approx 5$ phe is measured. Fig. 2 shows a typical charge spectrum when the light collected from both SiPMs at each end of the fiber is combined together requiring that both SiPMs collected something (logic “AND”). A mean of $N_{phe} \approx 10$ phe has been measured. The Sr90 is housed in a plexiglas collimator. We used collimators with different square hole sizes (no hole, 250, 500, 750 and 1000 μm). A scan of the relative position of the collimator hole with respect to the fiber was performed for each collimator hole size. The detection efficiency was extracted calculating the ratio of the fiber rate to the external trigger detector rate as a function of the scan position and selecting the highest obtained value. The results obtained for the different

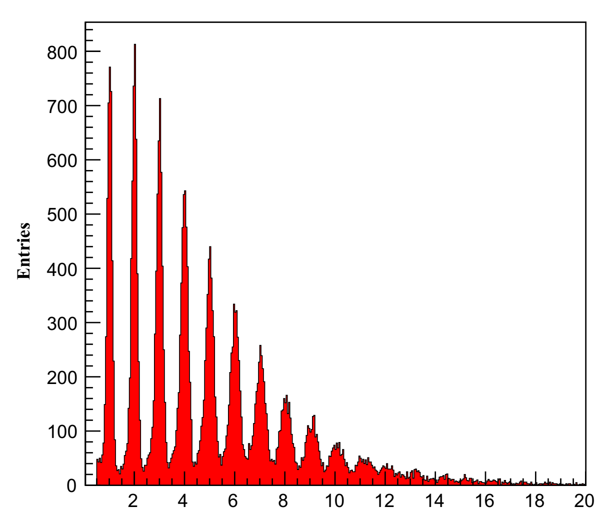

Fig. 1. Charge spectrum from light collected by a Hamamatsu 12571-100C SiPM coupled to a Saint-Gobain 250 μm square multi-clad fiber with a length of ≈ 25 cm.