Test of front-end electronics with large dynamic range coupled to SiPM for space-based calorimetry

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Abstract: Recent advances in the development of silicon photodetectors working in the Geiger mode (SiPM), open new perspectives in space-based or balloon-borne calorimetry. However, present SiPM devices suffer from a number of limitations, including the instrinsic dynamic range of the photodetector and its operational stability, that have to be overcome in view of their utilization in ionization calorimetry. Test results are presented on the readout performance of a SiPM prototype, optically coupled to scintillating fibers, and connected to low-noise front-end electronics with large dynamic range.

Introduction

The development of Geiger-mode silicon photodectors is being pursued by many different research groups and manufacturers. These devices are known with a number of different acronyms; in this paper, we will refer to this class of sensors as Silicon Photomultiplier (SiPM).
The SiPM device [1, 2] consists of a matrix of Geiger-mode Avalanche Photodiodes with resistive quenching, connected in parallel into a single readout element. The SiPM allows to count the number of photons interacting with the sensor up to a saturation value that depends on the total number of diodes in the array.
Given its excellent single-photon detection capabilities, the SiPM appears to be a realistic candidate for the implementation of large-scale scintillating fiber-tracking. In fact, this technique suffered, for many years, of the problem that the detection of very low light levels required photodetectors working at cryogenic temperatures, as in the case of the Visible Light Photon Counter (VLPC)[3].The silicon photomultiplier can instead be operated at modestly low temperatures or, in some cases, even at room temperature. Being modestly affected when operating in a magnetic field, the SiPM was immediately proposed as a viable solution for photodetection in magnetic spectrometers, where the presence of a stray field, at the photodetector location, implies the use of mesh-photomultipliers or, if the intensity is too large, forbids their use. The possible applications of SiPM, as a natural candidate to replace conventional photomultipliers, in calorimetry at accelerator and future collider experiments, is being investigated by a number of groups.
The very fast rise time of its signals makes the SiPM also very attractive for the time-of-flight (TOF) technique. Another possible application of SiPM in nuclear instrumentation, is the detection of the faint rings of Cherenkov light, produced by the passage of a relativistic particle in a suitable radiator, and imaged in a Ring Imaging Cherenkov (RICH) detector.
In the above applications, the number of detected photoelectrons is a critical parameter and a possible saturation of the SiPM signal is not an issue. On the contrary, the limited dynamic range of the SiPM may impose severe constraints to the design of a high energy calorimeter based on this photodetection technique.
The SiPM devices, available today, exhibit a large dark-count rate, a limited dynamic range

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and a gain that depends critically on temperature and bias voltage. Also, the large dark current at operating conditions (a few μA) requires care in the specification of the front-end electronics to keep the noise at an acceptable level.

In this paper, we report on some preliminary measurements with SiPM devices that were made to understand the possible limitations to their use in the design of calorimeters for space or balloon-borne instruments.

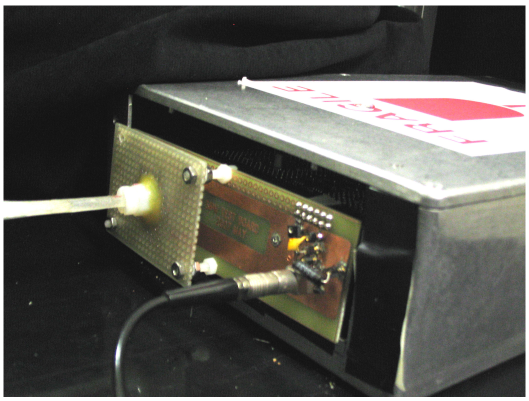

Figure 1: Laboratory test : one SiPM is optically coupled to a bundle of scintillating fibers.

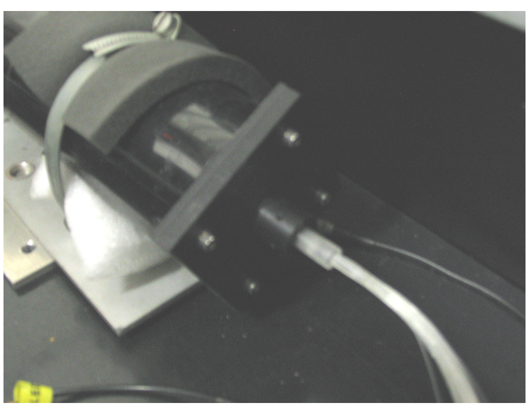

Figure 2: The same bundle of scintillating fibers connected to a conventional photomultipier.

Preliminary tests with SiPM

In the following, we report about measurements carried out in our laboratory with 1 mm $\times$ 1mm (SSPM-0611B1MM) and 2 mm $\times$ 2 mm (SSPM-0611B4MM) devices from Photonique (Switzerland), optimized for operation with blue light. The total number of pixels of the smaller SiPM is around 500 with a fill factor in excess of 70%. The gain can be varied from about 0.4 to $1.8 \cdot 10^5$ by biasing the device within 1 V above the breakdown voltage at 22°C. The larger area SiPM has $\sim$ 1700 pixels. The sensitive surface of both devices is protected by a transparent epoxy. This allows the use of optical grease to ensure a good coupling between the SiPM and fibers.

A bundle of scintillating multi-clad fibers with 0.5 mm diameter (Bicron BCF-12MC) were glued together in a region, a few centimeters long, on each side. Both ends of the bundle were then diamond-milled and polished. One side was optically connected to a SiPM, while the opposite end was coupled to the photocatode of a conventional photomultiplier (PMT). We illuminated the scintillating fibers either with UV light from a LED or we exposed them to a radioactive source. In this way, we could monitor the intensity of the scintillating light, using the PMT as a reference, and measure the relative response and efficiency of the SiPM. The experimental layout is shown in Fig. 1 and Fig. 2.

The front-end electronics and noise measurements

When connecting the SiPM to a charge-amplifier followed by a CR-RC shaper, the contribution to the "parallel" noise of the system, caused by dark current I_{dark} fluctuations, is important, given the relatively large value of I_{dark} (order of a few μA for a SiPM to be compared with nA in a silicon sensor). The noise variance is expected to scale linearly with the average dark current and with the integration time of the front-end electronics (FE). Therefore, integration time should not be too large, in applications where the contribution of the "parallel" noise exceeds the one from the "series" noise. In our early tests of SiPM, we decided to use the available front-end electronics that we had developed for the readout of (pixelated and strip) silicon sensors [4, 5]. The aim was to measure the noise figure of the system and to evaluate its possible use for calorimetric applications.

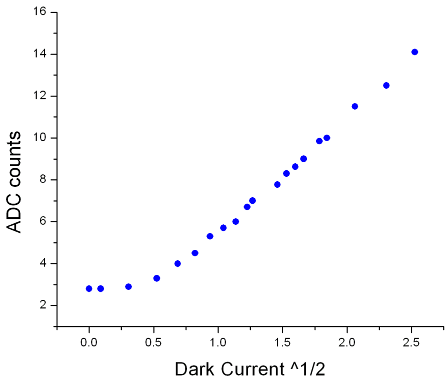

Figure 3: Pedestal RMS noise vs. SiPM dark current (μA).

The FE board used during the tests, was equipped with two ASICs of the VA family (HDR14.2) with a shaping time of about 1.8 μs, optimized for positive polarity, for a total of 64 channels. When disconnected from the SiPM, each channel had an RMS noise around 3 ADC counts, that translates into approximately 0.8 fC. When the FE electronics was connected to the SiPM, and below the breakdown voltage V_b, the RMS noise remained constant at the 0.8 fC level. It started increasing when the SiPM entered the Geiger-mode region. In Fig. 3 the RMS width of the pedestal is plotted versus I_{dark} while the latter was varied by changing the bias voltage. During all tests, the SiPM dark current was constantly monitored using a Keithley 6487 picoammeter. The RMS noise was found to scale as the square root of I_{dark}, as expected when the "parallel" component of the noise is the dominating source.

Measurements on SiPM saturation

The SiPM response is directly proportional to the total number of fired pixels per event, irrespective of the number of photons impinging on the same pixel. Therefore, saturation is expected to occur when the photon density exceeds a fraction of the total number of pixels per unit area, available for photodetection. Given N_{eff} pixels, defined as the effective number of pixels covering the illuminated area, the number of fired pixels N_{fired} is expected to scale as $N_{fired} = N_{eff}(1 - e^{-N_{pe}/N_{eff}})$ where N_{pe} is the average number of detected photoelectrons. The latter depends on the Photon Detection Efficiency (PDE) of the device.
By illuminating a single scintillating fiber with UV light, the response of the SiPM was plotted in Fig. 4 versus the response of the PMT to the same fiber (the signal from the PMT was AC coupled, via an interface board, to the same front-end and readout chain used for the SiPM). The number of photoelectrons detected by the PMT were estimated (to first order) by the ratio $\frac{\mu^2}{\sigma^2}$ where μ and σ^2 were the average and variance of the PMT pulse height distribution recorded for each data point. We estimated about 218 micro-cells were illuminated when the scintillating fiber was optically in contact with the SiPM sensitive surface. The response of the SiPM was found to reach 90% of the saturation value for N_{pe} larger than about 100.

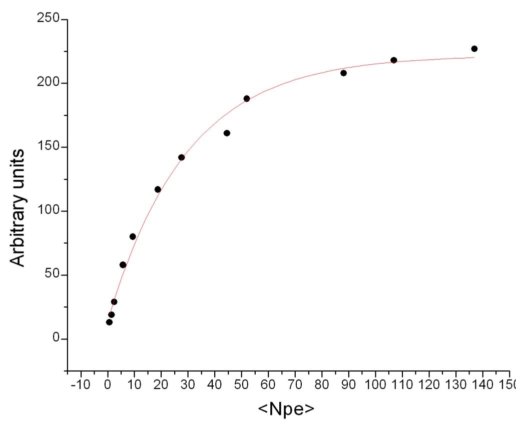

Figure 4: SiPM response plotted versus the PMT response when the fibers were excited with UV-LED light. The saturation of the SiPM follows the predicted behaviour (solid line).

Application to space-based or balloon-borne calorimetry

The use of SiPM for calorimetry is very appealing for a number of reasons. Compact and rugged, insensitive to magnetic fields, SiPM devices can reach the single photoelectron discrimination and achieve a good PDE, without requiring high bias voltages. This is an advantage for balloon payloads with no pressure vessel (the average atmospheric pressure at typical flight altitude is a few mbar) where conventional PMTs or Hybrid Photo Diodes (HPDs), have to be potted to prevent corona discharges.

However, present SiPM devices have a number of minor drawbacks. Uniformity in the response of SiPM units, delivered from different production batches, is not to be expected, at present. Therefore, each unit has to be calibrated and its gain monitored, invididually. The problem of gain dependence with temperature and bias (a stability within a few millivolts is required) can be technically solved, but probably requires monitoring of the dark current of individual (or small groups of) channels and in-flight calibrations with random triggers.

The problem of signal saturation may become an issue for calorimeters designed to reach very large energies. Let us assume, as an example, an energy deposit of 1 MeV per photoelectron in a cell of a SciFi sampling calorimeter and a realistic scenario where the SiPM saturation occurs when a few thousands pixels are hit. As a rule-of-thumb we may assume that a safe working region, where the SiPM non-linearity can be mapped and corrected for, extends approximately to a number of photoelectrons not much larger than half the number of the illuminated pixels. Then, using a large area SiPM with, say, 8000 to 10000 pixels, one could expect to reach saturation when the energy deposit per calorimeter cell exceeds a few GeV. If larger deposits are expected, the light from each calorimeter cell may have to be split up and fed (with different optical gains) into independent SiPM units. This may imply a large total number of SiPM units and readout channels, hence the need of low-power FE electronics .

A second difficulty comes from the noise inherent to the SiPM dark current. In order to keep the calorimeter's energy threshold sufficiently low, the noise, at channel level, has to be minimized. Therefore, the contribution due to parallel noise should be reduced (e.g.: decreasing the integration time of the front-end stage and/or operating the device at lower temperature).

Conclusions

Preliminary tests with silicon photomultipliers confirmed the appealing features of these devices, but also showed a number of limiting factors that have to be taken in serious consideration in the design of calorimeters that plan on using this kind of photodetectors.

Acknowledgements

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