SiPMs FOR BEAM INSTRUMENTATION. IDEAS FROM HIGH ENERGY PHYSICS

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Abstract

Silicon Photomultipliers (SiPM) enable fast low-level ight detection and even photon counting with a semiconductor device. Thanks to a now matured technology, SiPMs can be used in a variety of applications like: Medical imaging, fluorescence detection, range-finding and high-energy physics. We present different possible application of SiPMs for beam instrumentation. First, we discuss timing properties of SiPMs, and how to optimize them for high rate environments enabling photon counting. This requires to understand the dependence of SiPM pulse shape on its configuration (total area, cell size, capacitances, etc.) and analyse dedicated front end electronics techniques. Finally, based on the experience of several projects aiming to develop trackers for high-energy physics, we present some ideas to develop beam monitoring instrumentation based on SiPMs.

INTRODUCTION

The two main applications of photo-sensors for the detection of elementary particles are the scintillation detectors and the Cherenkov radiation detectors. Scintillators have been extensively used in calorimeters, and recently also in trackers based on scintillating fibres. Time of flight measurement often requires scintillators detectors as well. The most classical example of Cherenkov detector is the Ring Imaging Cherenkov (RICH), used for particle identification.

The photo-sensor requirements are different according to the specific detector. Usually, RICH detectors require blue and Ultra-Violet (UV) sensitivity and single photon detection. On the contrary, scintillator light yield is much higher and the emission is shifted to the blue/green region of the spectrum. However, calorimeters have large dynamic range, up to 100s or 1000s of photons, whereas scintillating fibre trackers are used for Minimum Ionizing Particle (MIP) signals, producing few photons.

For a long time the main photo-detector for such detection systems was the Photomultiplier Tube (PMT), which was created more than 50 years ago [1]. As alternatives to the PMTs, in the last decade, a new type of photo-detector was developed on the basis of the semiconductor technology, the Silicon Photomultiplier (SiPM) [2].

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SIPM TECHNOLOGY

The basic element of a SiPM is the Single Photon Avalanche Diode (SPAD) [3], consisting on an Avalanche Photo-Diode (APD) and a quenching element. If the bias voltage of an APD is greater than the junction breakdown voltage (this excess voltage is often called over-voltage), a charge multiplication process occurs and becomes a diverging self-sustaining process (Geiger regime). A quenching resistor, connected in series with the junction, is used to interrupt the avalanche: when the current in the junction is high enough to generate a voltage drop across the resistor close to the applied overvoltage (i.e. the difference between the bias voltage and the breakdown voltage), the current flowing becomes low enough that statistically the avalanche can be quenched and the junction is recharged.

A SiPM ([2], [4], [5], [6]) (also known as Geiger-mode avalanche photodiode, G-APD) is a device obtained by connecting in parallel several miniaturized SPADs (few tens of μm^2) belonging to the same silicon substrate so that the output signal of the SiPM is the sum of the SPADs outputs. The small SPADs in the SiPM are named microcells.

The gain of a SPAD is expressed as the ratio between the charge produced by the avalanche and the primary charge produced by the interaction of the optical photon within the device. Since the avalanche is interrupted when the voltage at the two sides of the micro-cell goes down to the breakdown voltage, the gain at the two sides of the micro-cell is can be expressed as the product of the SPAD overvoltage and parasitic capacitance.

The output of the SiPM is proportional to the number of cells that fired, provided that the number of incident photons is much smaller than the number of microcells and provided they are uniformly distributed across sensor surface. Since the overvoltage and cell capacitance uniformity can be quite accurate in modern production processes, an excellent separation between peaks in charge spectrum is achieved. This makes possible to count even tens of photons, which is clearly impossible with PMTs.

Photodetection efficiency (PDE) characterizes the probability that a device triggers on an incoming photon [4]. For a SiPM, PDE includes the transmissivity of the coating, the probability to hit the active area versus dead material between microcells (filling factor), and the probabil-

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ity to initiate an electron-hole production, often referred to as quantum efficiency.

SiPMs suffer from three main noise sources: dark counts, afterpulsing and crosstalk ([5], [6]). The noise in SiPM devices is mainly due to the dark count rate: an e/h pair can be thermally generated, triggering an avalanche in a micro-cell without an optical photon impinging on it. The dark noise rate depends on the working temperature and on the overvoltage, and it is directly proportional to the active area of the device. Other noise sources are correlated to other primary events triggered in one cell. Trapping of the carriers and their delayed release in the avalanche region can cause a second avalanche in the junction, named afterpulse [5]: trapped carriers can have a lifetime from tens to hundreds of nanoseconds and the second avalanche can be triggered also after the complete micro-cell recharge, increasing artificially the number of counted events. During the avalanche in a micro-cell, optical photons can be produced, whose interactions in adjacent micro-cells of the SiPM may generate optical crosstalk, introducing an additional noise component. The effect of crosstalk can be prevented with trenches (grooves surrounding each micro-cell), which can have metal-coated sidewalls [4].

SiPM technology has greatly evolved during last 10 years and currently can be considered as mature, although room for improvement still exists. Newest SiPM technologies guarantee a dark count rate of about 100 kHz/mm^2 at room temperature [8]. An optimal device would work with a large PDE (around 50 %), while having a crosstalk typically smaller than 10-20%. Currently, only few Hamamatsu devices achieve these performances [8]. A trade-off exists between PDE and crosstalk, since fill factor and overvoltage should be optimized in opposite directions for each.

A particular concern for particle accelerators and detectors is the radiation damage. It is well known that generating centers are created during irradiation which increase the leakage current. The bulk leakage current is multiplied in avalanche photodiodes (APD) by the gain factor and the resulting pulses are undistinguishable from photon-generated events. Bulk radiation damage in silicon detectors is primarily due to displacing damge. The damage is proportional to the Non-Ionizing Energy Loss (NIEL). Heavier particles produce greater damage. Neutron damage is the major concern for SiPMs. Consequently, an increasing rate of dark pulses as a function of the radiation dose is seen in SiPM [7]. Adverse effects of irradiation on other characteristic parameters of SiPM such as gain uniformity, afterpulsing or optical crosstalk probability would be also detrimental for a detector.

In any case, it is clear that SiPMs can compete with PMTs in nearly all applications. SiPMs are more compact, are not sensitive to magnetic fields, are more robust, are operated at lower voltages, potentially can achieve higher PDE and are better suited for mass production. Nevertheless, PMTs still have some advantages, namely: lower temperature dependence and lower dark count rate. But it is worth to keep in mind that temperature dependence of the SiPM is related to the breakdown voltage temperature dependence and, therefore, can be corrected by smart supply voltage control, as done in some custom and commercial systems.

FRONT END ELECTRONICS

To exploit at best the advantages of SiPMs they need to be read out via a dedicated multi-channel chip. A number of readout ASICs for SiPM readout can be found in the literature [15]. But we can identify some specific functions which a front end electronics for SiPM needs to perform:

- Adapt impedances. SiPM capacitances range from 30 pF to more than 1 nF. That means that low input impedance front end electronics is preferred, particularly for high speed applications.
- Shape the input signal. SiPM pulses typically have a long time constant associated to the recharge of the micro-cell. This may cause saturation or distortion because of pile up. Often, high pass or pole-zero cancellation filters are used to shape the pulse.
- Preamplify to optimize the Signal to Noise Ratio (SNR). Even if "nominal" gain is in the order of 10^6 only a fraction of the charge is used for fast read-out systems using fast shapers.
- Combine (sum) the signal of several SiPMs. In some applications large detection areas have to be covered. Since largest SiPM detection area is about 6x6 mm^2, smaller than largest PMTs, a common solution when large detection is required is to add the signal of several SiPMs. Direct parallel connection of SiPM devices has some drawbacks: extremely large capacitance (introducing limitations in speed and SNR) and difficult equalization of SiPM non-uniformities by overvoltage equalization.
- Equalize overvoltage. The breakdown voltage of SiPMs suffers from process variability, although fabrication processes have improved significantly. The non-uniformity of breakdown voltage is translated mainly in gain non-uniformity when several SiPMs are biased with the same power supply. This is particularly problematic when SiPM signals have to be added. For this reason, some circuits allow DC adjustment of the voltage of the input, which is connected to the SiPM anode or cathode.

An example of circuit implementing all the aforementioned functionalities is the Multiple Use SiPM Integrated Circuit (MUSIC) ASIC [9]. MUSICR1 performs several functionalities using the different output currents from the readout circuit, as depicted in *Figure 1*:

- Channel sum: The sum of the input signals is provided as a dual-gain output in differential mode using the high gain and the low gain currents from the readout circuit.
- Analog channels: 8 individual single ended analog outputs.

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- Digital channels: 8 individual digital outputs are obtained using a discriminator.
- Fast OR signal: A trigger pulse is provided by performing an OR between any selection of digital signals.
- Integrator current: 8 output currents for an external slow integrator.

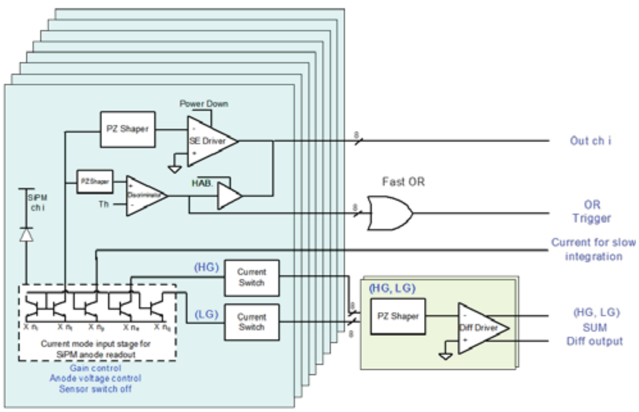

Figure 1: MUSIC block diagram [9].

For each individual channel, the user must select the analog or digital output since both signals share the same output PAD. Moreover, a selectable dual-gain configuration is available for each functionality, the channel sum and the 8 A/D outputs. The Pole-Zero (PZ) cancellation can be used or bypassed in any operation mode.

Other blocks are included to set the correct operation points of the circuit and configure several tunable parameters. For instance, individual SiPM pixel voltage control and switch off is possible by reducing the overvoltage by 4V. It is important to highlight that every block and channel can be disabled (power down mode) with a specific control signal.

Pole-zero cancellation can be applied to any input. Figure 2 shows the PZ cancellation response for a 6x6 mm^2 and 50 µm cell SiPM signal. PZ filter parameters can be adjusted as the pulse shape varies depending on the manufacturer, the SiPM size and microcell (pixel) size.

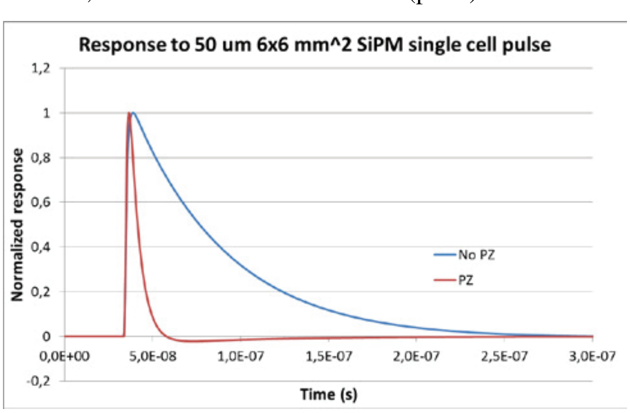

Figure 2: MUSIC Pole-Zero cancellation response for a 6x6 mm^2 and 50 µm cell SiPM signal.

MUSIC achieves excellent SNR, even with PZ cancellation as can be noticed in Figure 3. The SiPM is illuminated with a fast (50 ps FWHM) laser in low light level conditions. The illumination follows a Poisson distribution with an average of few photons. Discrete levels related to the number of fired cell can be easily distinguished in Figure 3. The PZ cancellation narrows down the SIPM pulse to 5 ns FWHM, when the input SiPM pulse FWHM was higher than 100 ns.

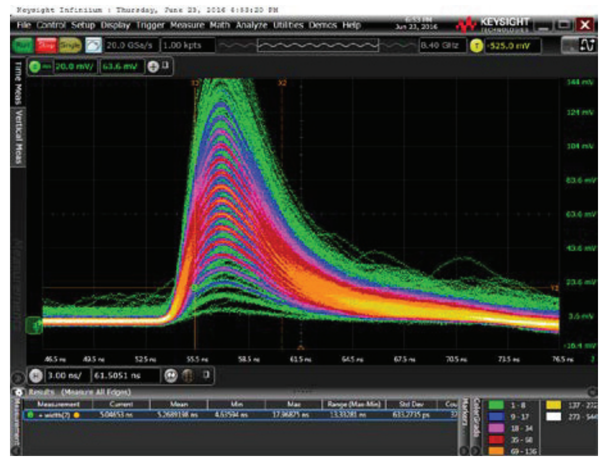

Figure 3: MUSIC analog output with PZ cancellation for low level illumination using a 3x3 mm^2 and 75 µm cell SiPM

MUSIC's low SNR allows clear identification of more than 10 photon peaks in the charge spectrum as shown in Figure 4.

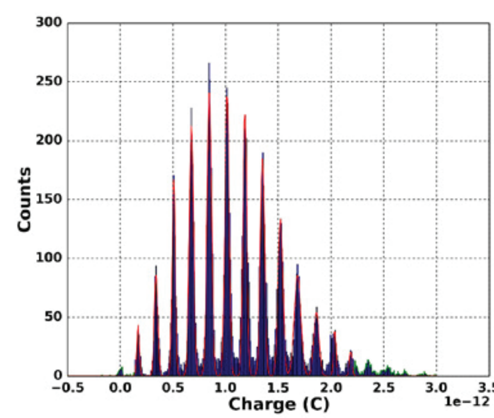

Figure 4: MUSIC charge spectrum with PZ cancellation for low level illumination using a 3x3 mm^2 and 75 µm cell SiPM

As said above, MUSIC individual outputs can provide either analog signal (as above) or a discriminated signal. The later is shown in Figure 5. The high SNR provided by MUSIC allows identifying the number of incident photons looking to the pulse width. The FWHM for a single photon is about 5 ns. The Single Photon Time Resolution (SPTR) of the combination of SiPM and MUSIC can be measured by looking to the RMS spread of the delay between the leading edge of the trigger signal and the leading edge of MUSIC discriminated output. The SPTR of SiPM connected to MUSIC is about 100 ps RMS. SiPMs can provide better time resolution than PMTs, although Micro-Channel Plate (MCP) PMTs can achieved

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SPTR as good as 30 ps. Nevertheless, the cost and fragility of MCP-PMTs limit its use to specific applications.

As a final remark on SiPM and Front End electronics technology, we should consider the so-called digital SiPM or Digital Photon Counter (DPC), which combines the sensor and readout electronics in the same chip [11]. It offers interesting possibilities but the read out is customized to specific applications and lacks from flexibility in many cases.

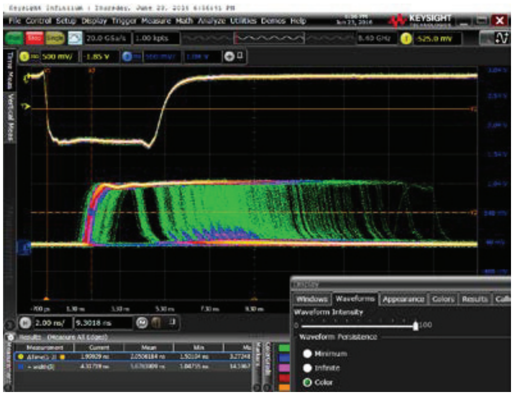

Figure 5: MUSIC discriminated output (bottom) with PZ cancellation for low level illumination using a 3x3 mm^2 and 75 µm cell SiPM. Laser trigger signal on top.

USE CASES IN HIGH ENERGY PHYSICS

Although SiPMs are scarcely used in currently operating detectors, many new projects and upgrades have already chosen SiPMs as baseline detectors.

As a first example we can consider the Scintillating Fiber (SciFi) Tracker, which is being built for the upgrade of LHCb tracking system [12]. The LHCb detector will be upgraded during 2019-2020 in order to collect data from proton-proton collisions at the LHC at higher instantaneous luminosities and to read out the data at 40MHz using a trigger-less read-out system. All front end electronics will be replaced and several subdetectors must be redesigned to cope with the higher occupancy. The current tracking detectors downstream of the LHCb dipole magnet will be replaced by the Scintillating Fibre (SciFi) Tracker. The SciFi Tracker will be constructed using 2.5 m long scintillating fibres and read out by Silicon Photomultipliers (SiPM) located outside the acceptance. The fibres have a diameter of 0.25 mm, are wound into ribbons with 5 or 6 staggered layers of fibres, and will cover a total active area of around 360 m^2. State-of-the-art multi-channel SiPM arrays are being developed to read out the fibres. A custom ASIC, the PACIFIC, will be used to digitise the signals from the SiPMs and additional front end electronics based on FPGAs will be used to reconstruct hit positions. There are a number of challenges involved in the construction of this detector: the radiation hardness of the fibres and the SiPMs; the mechanical precision required while building large active detector components; and the cooling required to mitigate the effects of radiation damage.

It has been seen that scintillating fibres will lose transmission [13] under irradiation. However, the literature describing this particular fibre is limited in the degree of damage in our radiation dose range. Multiple separate irradiation campaigns within the SciFi collaboration were undertaken to investigate the damage, irradiating the fibres with 24 GeV/c protons at the CERN-PS, 23 MeV protons at the Karlsruhe Institute of Technology, in situ LHCb pit irradiation, as well as gamma and x-ray irradiation [12]. The results are shown in Figure 6.

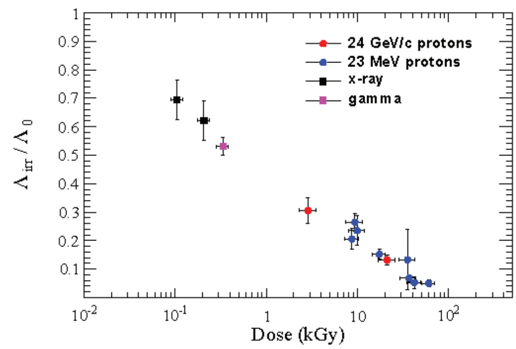

Figure 6: The ratio of attenuation length after irradiation to before as a function of dose for scintillating fibres for multiple source of ionizing radiation [12].

Anyhow, SiPMs are used in many other types of detectors [14]. SiPMs are used in the analog hadronic calorimeter (AHCAL) of CALICE prototypes for an ILC detector. SiPMs are also used in T2K electromagnetic calorimeter, in Belle II endcap detector and in CMS hadronic calorimeter upgrade [14].

APPLICATIONS IN ACCELERATOR BEAM INSTRUMENTATION

As said above, SiPMs could replace PMTs in nearly any possible application:

- For scintillator detectors we know they are used in calorimeters in HEP where a large dynamic range (up to 14-15 bits) is required.
- Cherenkov detectors. A high PDE (near 50 %) and enhanced near Blue/UV sensitivity make SiPMs excellent Cherenkov light photo-sensors.
- Single photon detectors and photon counting. Although the SiPM presents a long time constant related to microcell recharge time, the pulse can be narrowed down below 5ns after by adequate shaping. Moreover, a SiPM readout with a fast electronics presents a SPTR in the order of 100 ps.

Of course, PMTs are still a better choice when very low dark current is required, when the neutron radiation damage might be a concern or when very large photodetection areas must be covered with low pixelation.

An obvious application of SiPMs could be replacing PMTs in beam loss monitors based on Cherenkov light detection. Several works in that direction have been presented in IBIC 2016. A potential limitation in some environments is the SiPM dark count rate. An alternative approach would be to use scintillating fibres in coinci-

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dence, but as discussed above scintillating fibres are quite sensitive to radiation damage. Probably, additional R&D is needed to define the applicability of the SiPMs in beam loss monitoring.

SiPMs could find also an application in transverse profile monitors based on scintillating fibres [16] and similar devices.

Another possible application could be in Time Correlated Single Photon Counting (TCSPC) for beam filling pattern measurements [17]. The technique consists in the measurements of the temporal distribution of the produced synchrotron radiation using Electro-Optical devices, from where the filling pattern is inferred. SiPMs are already outperforming PMT performances [18]. The combination of high-performance SiPM and fast readout as MUSIC [9] reaches SPTR values in the range of 100 ps, lower than current systems based on PMTs.

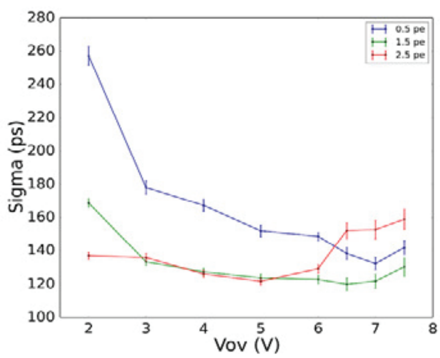

Figure 7: SPTR as function of the overvoltage for a 3x3 mm^2 and 75 µm cell SiPM readout by MUSIC ASIC.

CONCLUSIONS

SiPM technology has reached maturity and combined with adequate readout electronics might be applied in accelerator beam instrumentation. Possible use cases are optical fibre based beam loss monitors and TCSPC measurement of beam filling pattern, among other options.

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