TEST OF A SILICON PHOTOMULTIPLIER FOR IONIZATION PROFILE MONITOR APPLICATIONS

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Abstract

A samples of SiPM (silicon photomultiplier) has been tested as an elementary light detector for accelerated beam fast profile observation by using it in residual gas ionization profile monitors (IPM). Noise, sensitivity, dynamic range and timing parameter tests of SiPMs were performed. A possible procedure of the data acquisition and following signal reconstruction is discussed. A special attention has been paid to the fine time resolution counting mode with single photon detection. A dedicated signal normalizing and time-to-digit converter design was prototyped and tested. In addition some different modes of operation and optical schemes are discussed in this paper. It is shown that fast optical detectors like SiPMs also could be used for high performance profile measurements with spatial resolution compatible with CCD sensors.

INTRODUCTION

To provide a non-destructive beam profile measurement at modern ion synchrotrons and storage rings an advanced Ionization Profile Monitor (IPM) with improved spatial and time resolution is going to be developed in GSI [1]. Profile observation will be done by residual gas ionization electrons registration. Applied electric and magnetic fields will provide demanded time and spatial resolution. A two-stage MCP with phosphor screen output will be used as a primary signal intensifier. To realise a fast option of IPMs one need a faster detector than currently available CCD devices. As an alternative to a CCD an array of fast avalanche or p-i-n photo diodes was considered as detector in [2] as well as some requirements to operation conditions in analogue mode. A new type of solid state photo detectors named Silicon Photomultiplier (SiPM) shown in Fig.1 provides efficient light utilization.

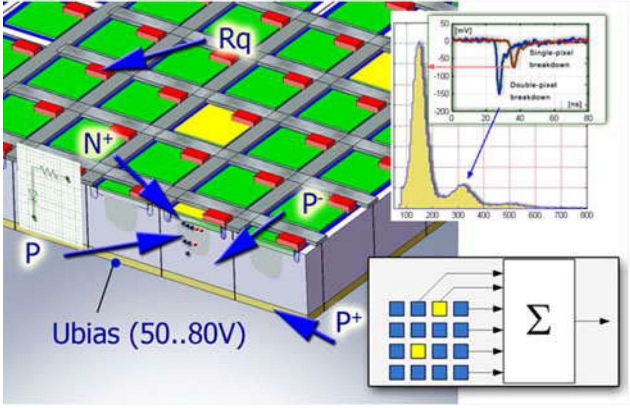

Fig. 1. SiPM is a matrix of avalanche diodes operating in Geiger mode and having common output.

A SiPM [4,5] is a multi-pitch silicon photodiode with a number of micro-cells (typical size of 20–30 μm) joined together on common substrate and working on common load. The operational bias voltage is 10–15% higher than the breakdown voltage, so each SiPM pixel operates in Geiger mode with avalanche current limited by individual polysilicon resistor located on the same substrate, with a gain determined by the charge accumulated within pixel capacitance. Each pixel multiplies the carriers created by photons or thermally by a factor about 10^6, the value close to that of photomultiplier. Actually, each SiPM pixel operates as a binary device, but SiPM upon the whole is an analogue detector, which can measure the light intensity within the dynamic range, determined by a finite number of pixels (~10^3 /mm^2).

SiPM have the following features that approve their use for IPMs: high gain (~10^6), same as in photomultiplier (PMT) but much larger than on Avalanche Photodiodes (APD) (~10^2) with Photon Detection Efficiency (PDE) same as for a PMT (~16%) with respect to the phosphor screen wavelength (350..470nm); photon counting capability; reduced requirements to the noise of the adjacent electronics; small time jitter (δτ 100 ps); short recovery time (~3ns); good temperature and voltage stability (much better than for APD); insensitivity to magnetic field ; low bias voltage (~50V) (comparable to PMT's ~1kV); compactness and robustness; low cost and simplicity of measurement system.

Modes of operation

Linear photocurrent detection

Despite every pixel of the SiPM operating in Geiger mode, an entire device may be used as a linear light detector.

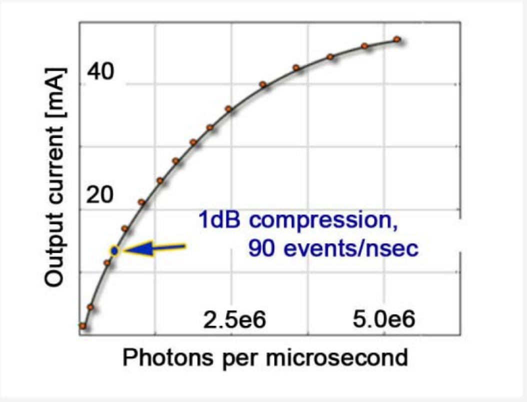

Fig. 2. SiPM's input-output transfer characteristics in analog mode.

Due to the higher internal amplification SiPMs better suited for low noise applications than other types of photodiodes. Fig. 2 shows the conversion curve of the 1000-pitch SiPM. The SiPM features in the linear mode in the frame of IPM applications are discussed more detailed in [3].

Counting mode

The counting mode provides a separate registration of incoming events, keeping the information about time and position of every light spot on the phosphor screen of the IPM. Obviously a higher performance of an adjusted electronics is required than in the case of the photocurrent registration.

The pulse counting operation is natively matches the discrete nature of incoming signals of IPMs. There are also no needs to care about equalising gain coefficients over all channels. No 'imaging quality' of the MCP is required. There are no data losses due to the non-controlled averaging of several pulses.

Reduced quality profile measurements are allowed even with a small amount of events per profile. Fig. 3 shows the confidence interval for the low-statistics and low-resolution case.

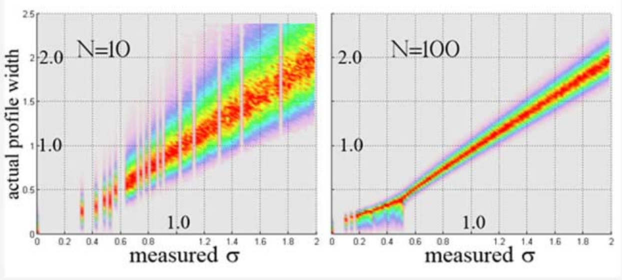

Fig. 3. The confidence intervals for 90% probability for number of samples per profile N equal 10 and 100. For higher σ the interval may be estimated as $1/N^{½}$.

A performance of the counting mode for single-shot measurements is defined by the residual gas pressure. Usually this parameter is not well controlled. This produces certain problems with the dynamic range adjustment. Hopefully for periodic processes the adjustment could be done by the changing of the averaging time.

Encoder mode

The high sensitivity of SiPMs allows using complex optical solutions with relatively high light losses. It is also possible to distribute the light from one event over few detectors obtaining some new possibilities for a profile registration. Using a mapped fiber encoder similar to one shown in fig. 4 allows a higher spatial resolution with a smaller amount of photodetectors. One can use additional bits for error correction to separate the IPM events from the SiPM dark count pulses.

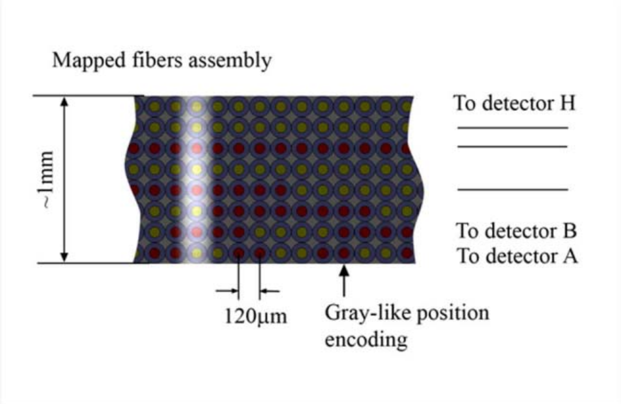

Fig. 4. Spot position encoding by using mapped fibers assembly.

The high sensitivity of the SiPM should be supported by high performance optical system. To simulate complex optical assemblies, an optical system toolbox was designed for MATLAB. It allows to estimate a behaviour of complex optical systems including cylindrical geometry, determine image quality, light losses etc. An example of the simulated system, which has been designed to be used with mapped fiber assembly, is shown on fig. 5. This optical system uses cylindrical lenses due to the principal system non symmetry. Triplet geometry gives freedom to focus the image independently in horizontal plane and defocus it in vertical plane. The simulation shows for the given geometry a light transmitting efficiency from the phosphor to a single fiber about 15e-6 with 20% variation and adjacent channel crosstalk up to 40% in an assumption of a 0.2mm original spot size. This is nearly sufficient for using in a system, equipped with a two-stage MCP and fast E36 phosphor. Due to the limited field of the depth, about 0.5mm, a high resolution encoder must be installed in parallel with phosphor plane of the MCP.

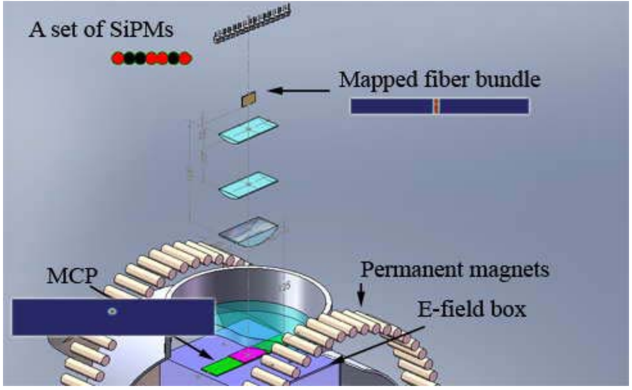

Fig. 5. The simulated optical layout for counting operation with mapped fiber position encoder. The central part of the MCP could be observed with 0.15mm accuracy with 300Mcps performance.

Test layout

A few samples of the SiPM have been tested in the lab. The sensitivity, thermal and temporal gain stability, dark counts rate etc. were measured during the tests. Some electronic schemes were designed to find the most suitable solution for further IPM applications. The experimental layout is shown in fig. 5. A short light pulse produced by an LED was transmitted via glass fiber to the SiPM holder. This fiber additionally delays the pulse to avoid EMI signals from the pulse generator. Precise intensity regulation in 40 dB range was achieved by changing the distance between the fiber output and the SiPM. The output of SiPM was loaded with 50 Ohm 1GHz amplifier connected to oscilloscope or time-to-digital converter with 20ps LSB resolution.

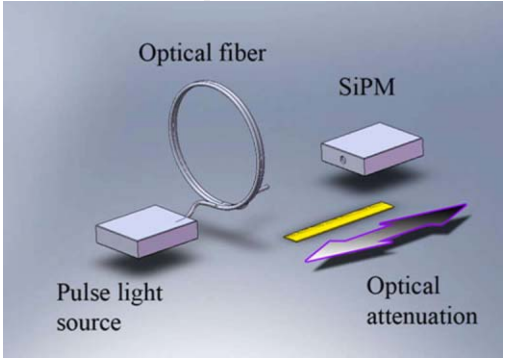

Fig. 6. A testing layout for the silicon photomultiplier's counting mode

A Hamamatsu wideband light receiver was used to control the pulse shape on the light source output. An example of a source signal reconstruction is shown on Fig. 7. To reproduce the form of the original signal the output of SiPM was captured on the screen of a digital oscilloscope in a long exposure mode. Integration of the data gives a good reproduction of the exciting signal with a rising front time of about 30ns. Fig. 7 shows the case of low intensity signal on SiPM input, so one can see single photon events and the dark count noise.

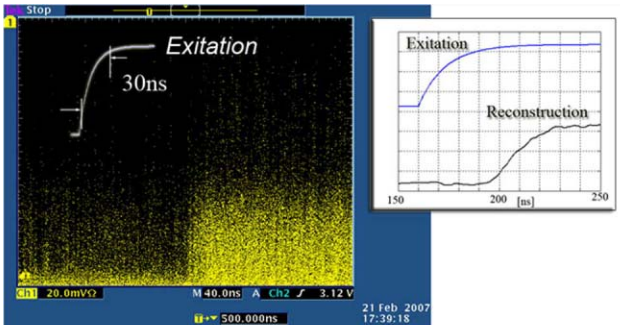

Fig. 7 Reconstruction of the rising front of the periodic excitation signal by averaging the output SiPM pulses.

For pulsed mode of operation our tests showed a time resolution down to 2 ns for periodic signals and this value obviously was not limited by the SiPM properties but by the characteristics of used environment. In the same time a using the SiPM in the counting mode for single-shot measurements without position encoding has no visible advantages in comparing with linear mode of operation.

The dynamic range of the presently available SiPMs in counting mode is limited by a relatively high dark count rate. Some types of SiPMs have up to 250kcps dark count in room temperature conditions. We also have tested SiPMs with different pulse discriminating levels to take off the pulses from single, double or triple-pitch breakdowns. This effectively decreases the dark count rate and gives a possibility to increase the dynamic range of the SiPM into higher intensities. Without that the dark count will hide pulses from phosphors with longer than 100ns decay time.

Conclusion

A SiPM is a well suited light detection device for ionization profile monitors to be used in event counting mode with relatively high count rate. This counting mode could provide 500MHz bandwidth for periodical processes and up to 10 profiles per microsecond with 10% of standard deviation accuracy for single-shot processes (local gas jet is required). To achieve a SiPM performance in single-shot operation a fast nanosecond-range phosphor type is required as well as a high performance multichannel electronic counters with adjustable discrimination level. For low input rate measurements with typical residual gas pressures a cooling down of the SiPM to -20..-40 C^{o} will be a good option for dark count elimination. Using an optical encoder in combination with a limited amount of SiPMs (or, with same success, in combination with a multichannel photomultiplier) allows reaching sub-millimetre spatial resolution by cost of some performance degradation in transient processes measurements.

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