Precision Timing Counter Based on Plastic Scintillator with SIPM as Photon Sensor

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***Abstract* - R&D studies of a timing counter based on plastic scintillator readout by silicon photomultipliers (SiPM) have been performed. The current voltage (I-V) characteristic and optical response studies of the SiPMs have been studied. Time resolution of the counter is measured with counter size 30 × 30 × 5 mm^3 and with two SiPMs connected at the two opposite sides of the scintillation tile. Optimum detector conditions have been searched with respect to variation in overbias voltage and discriminator threshold to achieve best time resolution. A time resolution (σ) of 188.8 ± 3.9 picosecond has been achieved in the present study.**

***Keywords*- Silicon photomultipliers, multi-pixel photon counter, scintillators, time resolution, optimum bias voltage, threshold scan and dark noise study.**

I. INTRODUCTION

Plastic scintillator detectors are undoubtedly the most often and widely used particle detection devices in nuclear and particle physics experiments. Fast timing response of these scintillators ([1], [2]) (their response and recovery time are much shorter relative to other types of detector) makes this device a popular choice for measurements where timing information is needed i.e., the time difference between two events. These scintillators can be coupled to silicon photomultipliers (SiPM) - the new generation photo sensors – to develop a detector for precise timing measurement. Ultrafast timing information is an essential parameter in many of the high energy nuclear physics experiments. For example, the experiments that are being planned by the PANDA collaboration ([3], [4]) at the upcoming international accelerator facility FAIR [5], Germany for double-hyper nuclei search and rare decay studies need the detectors to be operated at high luminosity mode (~2 × 10^{32} cm^2 s^{-1}) and the desired time resolution for Time-of-Flight system SciTil (Scintillator Tile hodoscope) detector [6] is of the order of 100 - 200 picoseconds. Here, the conventional vacuum PMTs are ruled out as the detector is to be operated inside a large magnetic field.

In addition to potential applications in high energy nuclear physics experiments, the fast timing properties of the silicon photomultipliers are of great interest in the medical diagnosis e.g., in the Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT) and development of PET/MRI (Magnetic Resonance Imaging) combo equipment ([7], [8], [9] - [11]). With the use of SiPM in time-of-flight PET, much better image quality and shorter scanning time can be achieved ([12], [13], [14]). Fast response of SiPM will enhance time-of-flight performance by measuring difference between times of arrival of the two gamma rays coming from the positron annihilation, thereby allowing a better determination of the depth-of-interaction.

The SiPMs are latest photon counting devices that show great promise in its usage as an alternative of the PMTs ([15], [16], [17]). The silicon photomultipliers, having high photon detection efficiency (PDE) and single photon response, are advantageous over the conventional PMTs due to their compactness in size, low operating voltage and insensitivity to magnetic field. The SiPM, also known as Multi-pixel Photon Counter (MPPC), is essentially an avalanche photo-diode operated in limited Geiger mode where the magnitude of a large gain (10^6) is determined by the internal diode capacitance and applied over-bias voltage. A SiPM consists of matrix of micro cells, known as pixels, with pixel pitch typically 25, 50 and 100 μm. Each micro cell acts as digital device where the output signal is independent of the number of photons absorbed. When all the cells are connected in parallel, the SiPM becomes an analogue device thereby allowing the number of incident photons to be counted. A detailed study of properties of SiPM can be found in references ([15], [16], [17], [18]) and references therein.

The primary motive of the present work is to develop a high precision timing counter based on plastic scintillator with SiPM readout. The study of optimum detector conditions for achieving best time resolution with respect to various parameters e.g., variation in the over-bias voltage and discriminator threshold is also a part of this work. The dimension of each scintillator is chosen sufficiently small so that the granularity of the counter can provide additional information on position (spatial resolution) when a large array of a scintillation detector/ hodoscope is constructed using these devices.

II. EXPERIMENTAL DETAILS

A plastic scintillator tile (dimension 30×30×5 mm^3) polished on all six faces was used. Ultra-Fast timing plastic scintillator [19] BC-422 (rise time 0.350 ns, decay time 1.6 ns, light output 55%) was chosen. MPPCs, having photosensitive area of 3 mm × 3 mm were coupled to the scintillator. The overall dimension of the MPPCs matches the dimension (width) of the tile. For better optical contact between the scintillator and photo-sensor, optical coupling grease [19] BC-630 was applied. The MPPC was held in position with aluminium reflecting tape in order to increase the probability that the SiPM captured the photons produced in the scintillator. Aluminium foil was used to cover all the faces of the scintillator for internal reflection of the light and finally it was wrapped with black foil for light tight. The tile was mounted inside a wooden black box. The counter was irradiated with electrons from (^{90Sr}/^{90}Y) β-radioactive source (E_e<2.28 MeV). The scintillation photons generated in the scintillator volume were seen by the photo sensor. For time resolution measurement, two sensors were coupled to the scintillator at two opposite ends. A schematic diagram of the setup is shown in Fig.1.

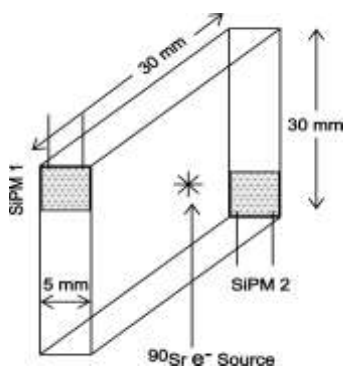

Fig. 1 Schematic diagram of the setup used for time resolution measurement. The plastic scintillation tile is coupled to two SiPMs at opposite sides for readout.

III. RESULTS AND DISCUSSION

At first, the I-V characteristic of several MPPCs was studied. The applied bias voltage and current were controlled by high precision digital multimeters. The breakdown voltage is observed to be around 70 - 72 Volts. SiPM properties are known [18, 20] to vary between different types and even within a batch of same types. The operational bias voltage was decided accordingly and a bias scan was performed to get the best results as discussed later in detail. It is to mention that low operating voltage of SiPM is a significant advantage over the traditional vacuum photomultiplier tubes where typical bias voltage is ~1-2 kV. The block diagram used is shown in Fig. 2 and a typical signal output of MPPC, with amplifiers make Photonique-SA [21] having signal amplification of 10X....20X, is shown is Fig. 3. Typical signal rise time observed is ~ 3 ns.

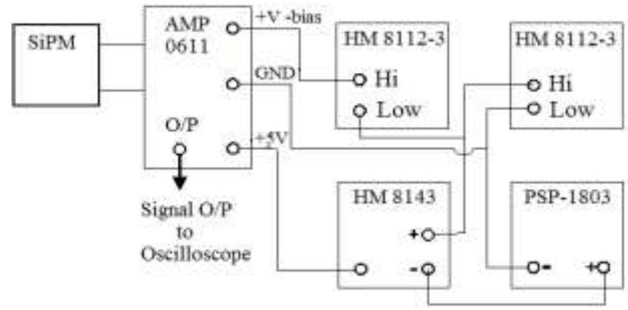

Fig. 2 Block diagram used in the present study. AMP-0611: amplifier make Photonique SA, HM_8112-3: precision multimeter make Hameg, PSP-1803: programmable DC power supply from Voltcraft and HM_8143: power supply make Hameg.

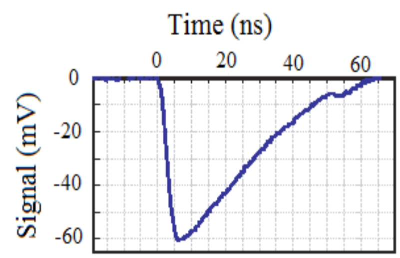

Fig. 3 The MPPC signal output taken with a digital oscilloscope.

A. Measurement of Time Resolution

The time difference between the scintillation photons reaching the two MPPCs was measured. A standard time coincidence set-up using Constant Fraction Discriminator (CFD) and Time to Amplitude Converter (TAC) was employed as shown in Fig. 4. Time calibration was done by introducing a known time delay between the start and stop signals. A VME based data acquisition system was setup and Linux based advanced multi-parameter data analysis package LAMPS [22] was used for online data collection and analysis. The best time resolution achieved in the present measurement, as shown in Fig. 5, is σ = 188.8 ± 3.9 ps with the scintillator BC-422 and MPPCs having photo sensitive area of 3 × 3 mm 2 and pixel size 25μ and 50μ.

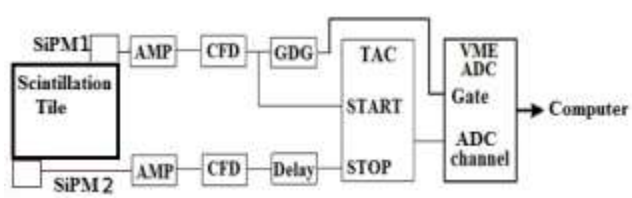

Fig. 4 Block diagram for the coincidence circuit used for time resolution measurement.

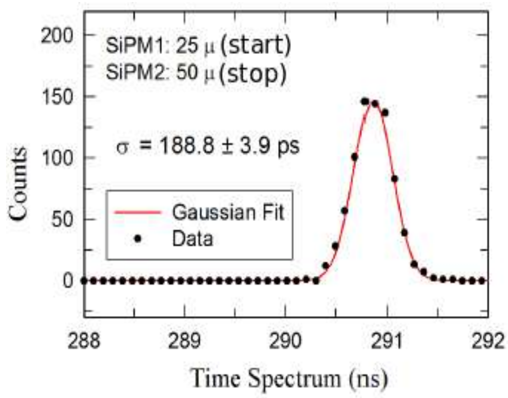

Fig. 5 Time spectrum obtained in the time resolution study.

B. Optimization of SiPM Operating Voltage and Discriminator Threshold

To gain a better understanding of the achieved time resolution, we have performed a series of coincidence timing measurements as a function of the SiPM bias and discriminator threshold. In Fig. 6 we plot results for threshold scan at a fixed bias voltage for the SiPMs. The operating voltages for the SiPMs were chosen for which the best timing resolution was achieved. A typical feature of all scans is that starting with lower threshold a systematic improvement in time resolution is observed as the threshold increases and it reaches an optimum value above which the resolution, however, starts gradually decreasing.

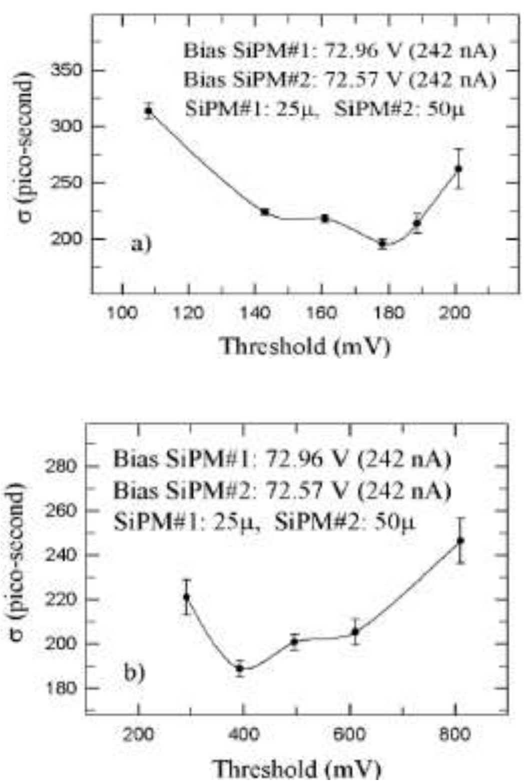

Fig. 6 Threshold scans for highest time resolution study. In (a) we varied the discriminator threshold for SiPM #1 while the discriminator threshold for SiPM #2 was fixed and in (b) we varied the discriminator threshold for SiPM #2 keeping the discriminator threshold for SiPM #1 fixed.

To search optimum operating voltage, the bias of the SiPMs was varied keeping the discriminator threshold at a fixed value. In Fig. 7 we show the plot in which the voltage for one of the SiPMs was varied keeping the voltage for the other one fixed. The bias scan exhibits an optimum value for which the resolution become maximum.

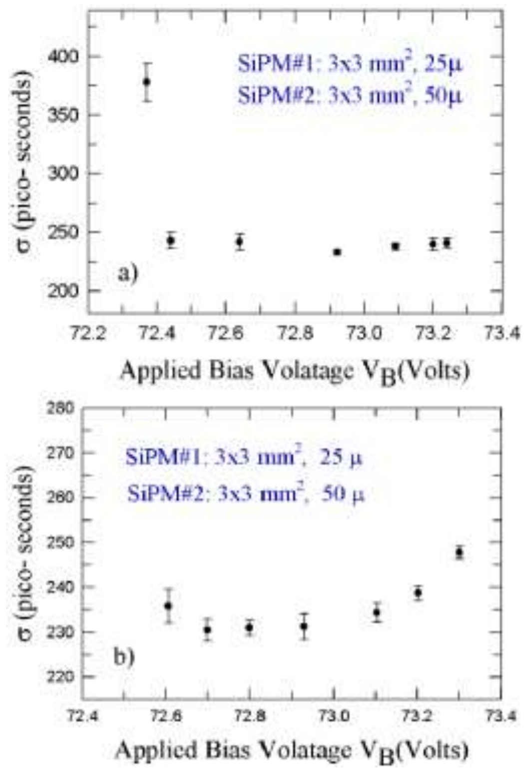

Fig.7 Search for optimum SiPM bias for highest time resolution in a coincidence measurement. (a) Variation of the SiPM #1 bias while voltage for SiPM #2 was kept fixed at 72.57 V / 242 nA. (b) Variation of the SiPM #2 voltage with SiPM #1 kept fixed at 72.96 V / 242 nA.

C. Study of Dark Noise Rate

We have also measured, in a separate run, the dark noise rate of the SiPMs against the discriminator threshold. The SiPMs were operated at the best bias voltage. As can be seen in Fig. 8, the graph exhibits a clear transition between individual photoelectrons (p.e.) that can be detected with decreasing threshold. The transitions from the first photoelectron to the second and the third are visible. For SiPM with pixel size 25μ and 100μ the effect is more pronounced. The dark noise rate at 1 p.e. is ≈ 10 kHz, at 2 p.e. ≈ 7 kHz and reduces to a very lower value for higher threshold. This study is very useful as for applications where sufficient number of photons are expected, appropriate threshold can be set to reduce the dark noise to a minimum label.

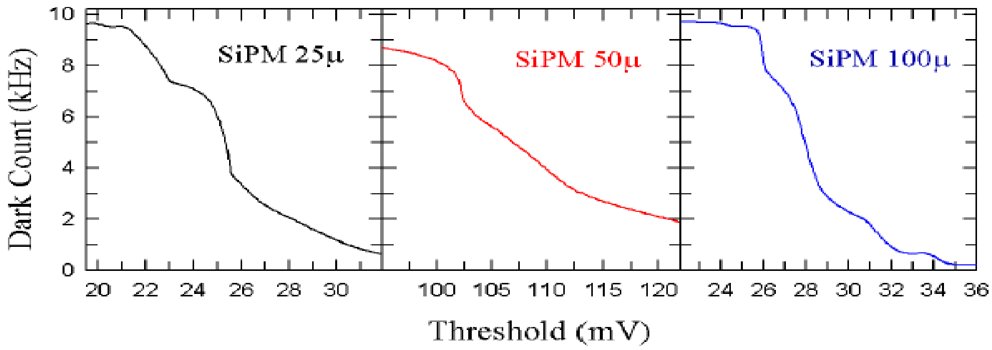

Fig. 8 Typical dark noise rate measured as function of discriminator threshold. Transitions from different photoelectron peaks are visible.

The silicon photomultipliers are also having excellent photon counting resolution. In an earlier study [23], a number of photo peaks (1p.e. to up to 7p.e.) were observed using low intensity laser light. The spectral sensitivity response i.e., photon detection efficiency of some of the SiPMs was also studied as a function of wavelength of the incident photon. These sensors are observed [23] to have wide wavelength response ($\lambda \sim 400$ - 800 nm) peaking around the visible blue to green light region.

IV. CONCLUSION

The present study with a timing counter based on plastic scintillator (dimension $30\times30\times5$ mm^3) readout by silicon photomultipliers (with photosensitive area of $3\times$ 3 mm^2) yields a time resolution of 188.8 ± 3.9 ps. Optimum detector conditions e.g., highest time resolution versus over-bias voltage and discriminator threshold have been studied. Such a device can be used to construct a large array of scintillation detector/ hodoscope where precise timing information is needed. With the presently chosen smaller size of the individual scintillator tiles, additional information on the position (θ, φ) can be obtained and can be used to improve the reconstruction of event tracking. The use of SiPM is advantageous that the detector can be operated inside magnetic field where the use of conventional PMTs is prohibited. The silicon photomultipliers are new generation photon detectors, the present R&D studies are expected to provide valuable information in this field that has important applications in several areas of basic research as well as in nuclear medical imaging. In the TOF-PET scanner, the idea is to use time-of-flight information in PET image reconstruction to improve the image quality. Here the arrival time of the 511 keV photons are to be measured very preciously to determine the location of positron annihilation. With the time resolution of 188 ps achieved in this study, a spatial resolution better than 3 cm can be achieved.

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