Investigation of a silicon photomultiplier and comparison with a traditional vacuum photomultiplier

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Abstract

Silicon photomultiplier devices (SiPM) were investigated under laboratory conditions as a possible a front-end detector system for the electromagnetic barrel calorimeter of the GlueX Project at Jefferson Laboratory, USA. The main parameters of the SiPM have been measured and compared with a traditional two inch vacuum photomultiplier tube. The energy spectrum and the timing resolution of signals generated by minimum ionizing particles detected in 4-m long Kuraray scintillating fibers were investigated with the SiPM and the PMT. The SiPM has a better timing resolution at least by factor of two and significantly better energy resolution in comparison with a PMT. Moreover, the SiPM has a gain comparable to that of a PMT, it requires a simple electronic circuit and is not sensitive to magnetic fields. These performance characteristics allow us to conclude that it is possible to use the SiPM as front-end detector for a barrel calorimeter.

Keywords: Silicon photomultiplier, scintillating fiber, barrel calorimeter.

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I. INTRODUCTION

The goal of the GlueX/HallD experiment [1] at Jefferson Laboratory in Newport News (Virginia, USA) is to search for evidence of gluonic excitations manifested in exotic hybrid vector mesons with mass up to 2.5 GeV/c^2 using linearly polarized photons of 8 - 10 GeV energy. The decay products of the produced mesons must be identified and measured with good resolution and with full acceptance for all decay angles. As such, the GlueX detector system must have the capability of measuring the emission angles and energies of neutral particles and the four-momenta of charged particles with good overall resolution to allow for a complete kinematic reconstruction of events and subsequent partial wave analysis [2].

The electromagnetic barrel calorimeter (BCAL) is a crucial GlueX/HallD detector subsystem. BCAL will be positioned immediately inside the super-conducting solenoid, which constrains its outer radius to be 90 cm, and will be approximately 4 m long and 25 cm thick. The calorimeter will be constracted with at least 4 m long scintillating fibers 1 mm in diameter embedded in a lead matrix. The readout system has to collect the scintillation – with peak emission in the range 350 - 500 nm – from about 3.2 m^2 of active surface of the barrel calorimeter. As a result, the front-end detector and the readout system have to have sufficiently good energy resolution (at least to be better in comparison with a calorimeter resolution determined as $\frac{5\%}{\sqrt{E(GeV)}}$ [3]) and adequate time resolution. For example, the requirement of 10 cm spatial resolution translates into σ=150 ps for a Gaussian fit of a timing spectrum. The anticipated count rate of events is about 10^6 events/s within the magnetic field created by the superconducting solenoid with a central value greater than 2 T.

Traditional vacuum photomultiplier tubes (PMT), hybrid photo-diodes (HPD) and silicon photomultipliers (SiPM) have been investigated [4 and 5] as possible front-end detectors, whereas the HPD and the PMT have proven unsuitable, the most promising results were obtained with the SiPM.

II. SILICON PHOTOMULTIPLIER

The SiPM is a novel type of avalanche silicon photodetector that operates in a Geiger mode [6 and 7]. It is a multi-pixel photo-diode with a large number of micro pixels (typical size of 20 - 30 μm) joined together on a common substrate and under a common load.

The photodiode has a multi-layer structure with different doping levels. As a result, within the thin depletion region between p^+ and n^+ layers, a very high electric field of about $5{\cdot}10^5$ V/cm is created, with the right conditions for a Geiger discharge mode to take place. The operational bias voltage is 10 - 20 % higher than breakdown voltage, with typical supplied bias voltage of 50 - 60 V. The diode is reverse biased to increase the field in the depletion region. The thickness of the depletion region is 4 - 6 μm and determines the light absorption.

Each pixel is electrically decoupled from each other and operates in a Geiger mode, limited by the charge accumulated in the pixel capacitance. The Geiger discharge ceases when the voltage drops down to values below the breakdown value due to the external resistor on each pixel. Each pixel detects and amplifies the charge from a photon independently of all other pixels and its signal does not depend on a impinging number of quanta that fires the pixel in a Geiger mode.

The gain for a single pixel is determined by the accumulated charge in the capacity of the pixel (typically, C_{pixel}=100 pF) and depends from a relative over-voltage:

$$Q=C_{pixel}\cdot(V_{bias}\text{-}V_{breakdown}),$$

where V_{bias} is the supplied bias voltage and $V_{breakdown}$ is the breakdown voltage.

The single pixel gain is approximately 10^6, roughly the same order of magnitude as that of a traditional PMT. While each pixel operates digitally as a binary device - because all SiPM pixels work together on a common load and there is a large number of pixels - the output signal is a sum of the signals from all pixels registering a "hit". Thus, the SiPM, as whole, is an analogue detector that can measure the incident light intensity. The distribution of the voltage across the depletion depth of 4 - 6 μm is such that for only a fraction of the depth (1 - 2 μm) the former exceeds a value sufficient for Geiger discharge creation, and therefore, the Geiger discharge is contained within this limited region. As a result, its duration is very short, a few hundreds of ps, resulting in typical rise times of 1 ns.

The photon detection efficiency for a SiPM depends on the quantum efficiency and a geometrical factor:

$$\eta = \text{QE}\cdot\varepsilon,$$

where η is the photon detection efficiency, QE is the quantum efficiency and ε is a geometrical factor.

The geometrical factor is a ratio of the sensitive area (as defined by the total active pixel area) to the total area. This value does not depend on wavelength and is a constant for each SiPM. In our case, the geometrical factor was 0.3 for all SiPM's investigated. The quantum efficiency is a function of incident wavelength of light and has a maximum in the $500 - 600$ nm region, decreasing monotonically for lower wavelengths.

The photon detection efficiency (η) for the SiPM is about 20 % for λ=550 nm, a value considerably larger than that of a PMT. For example, the quantum efficiency for the Burle 8575 PMT is about 5 % for the same wavelength. However, for λ=400 nm, the SiPM has a lower value of η than a PMT. Thus, the SiPM is more sensitive in the yellow-red region of wavelength in comparison to a PMT.

Due to its high gain, the electronics noise of the SiPM is negligibly small and the main source of the noise is the dark rate. The SiPM's used in our tests were developed and produced by the Moscow Engineering and Physics Institute (MEPhI). The specific SiPM's had 1000 pixels in each detector covering the 1 mm^2 sensitive area and the supplied bias voltage was 50 - 60 V. The total number of pixels defines the dynamic range of the photodetector.

III. TEST WITH A NITROGEN PLASMA DISHARGE TUBE

The purpose of this work was the investigation of SiPM's as front-end detector for the barrel calorimeter readout system, as defined by the requirements of the GlueX/HallD Project. Specifically the SiPM's were investigated under the following two conditions:

- detection of incident light of high flux intensity, where about 200 - 500 SiPM pixels registered a hit, but the signal was not saturated;
- detection of light of lower photon flux intensity in which case only few pixels registered a hit. This regime corresponds to few-photon counting condition.

FIG. 1: The shape of pulses from SiPM (left) and PMT (right). A light flasher (Optitron Inc.) was used as a light source. The high voltage for the PMT was 1900V and the bias for the SiPM was 55.5 V.

A. High Light Intensity Test

An Optitron nanosecond broad spectrum optical pulse radiator (Model NR-1A) with a Nitrogen Plasma Discharge Tube [8] was used as a source of light for the SiPM investigation in a high light intensity regime. The light pulses had a 1 ns rise time and a few ns pulse duration. A clear pure fused silica fiber of 5 m length was used to transport the light from the Optitron plasma discharge tube to the sensitive surface of the SiPM. The light intensity emitted from the this tube could be varied within a broad range of amplitudes.

The light pulses were measured with the SiPM as well as with a 2$''$ Burle PMT (model 8575). This was done for comparison and monitoring purposes. Pulses from the SiPM and the PMT were measured with the Tektronix TDS5104 digital oscilloscope as shown in Fig. 1. The left and right pulses are signals from the SiPM and the PMT, respectively. The supplied high voltage to the PMT was 1900 V white the bias for the SiPM was 55.5 V. The signals from the SiPM and the PMT have a similar structure but the rise time for the SiPM is 1 ns, as opposed to 4 ns rise time for the PMT. The signal amplitude for the SiPM is around 300 mV, which implies that an external amplifier is not required. That signal corresponds

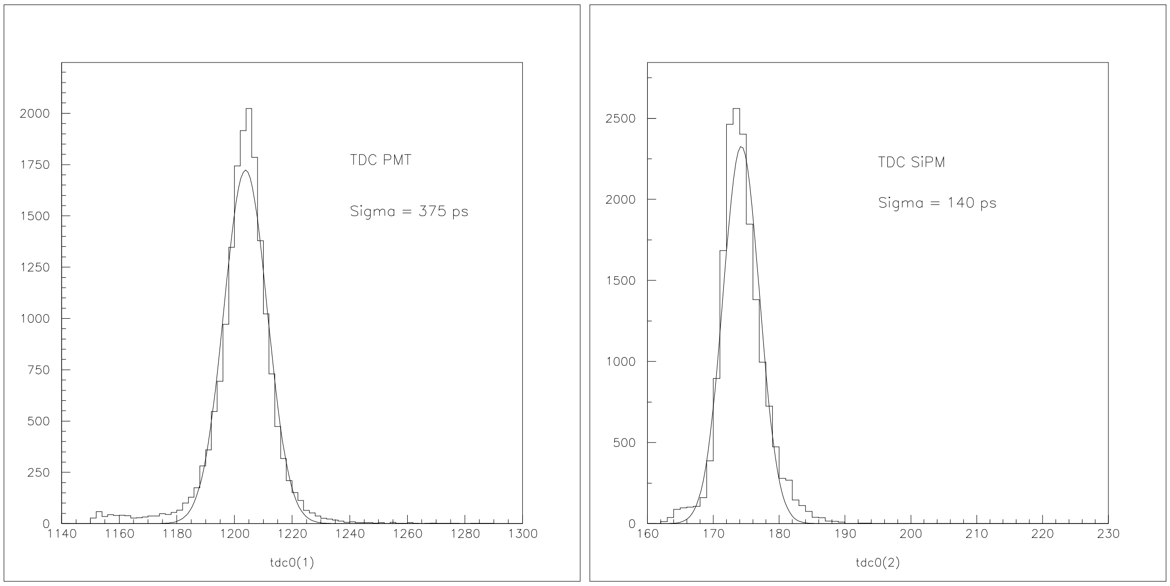

FIG. 2: The timing distributions of pulses obtained from a PMT (left) and a SiPM (right). The spectra were fitted with a Gaussian function.

to about 200 - 300 pixels registering a hit. The signals from the PMT and the SiPM were each split in two, with one branch fed to an ADC (LeCroy 2249A) and the other was fed to a Constant Fraction Discriminator (CFD Tennelec TC455) whose output was then fed to a TDC (LeCroy 2228A) unit.

The signal from the SiPM exhibited no saturation effect as concluded from the linear dependence of its ADC amplitude versus light intensity. The incident light intensity from the Optitron unit was monitored with the $2''$ PMT. The timing distributions of both are shown in Fig.2. The left and right panels correspond to the time distributions of pulses obtained from the PMT and the SiPM, respectively. The spline line is a Gaussian function.

In this measurement, the trigger signal from the plasma discharge unit acted as the "start" signal for the TDC unit. One notes that the time distribution for the SiPM has a σ which is at least half of that from the PMT distribution. In Fig.2, the SiPM exhibits a σ = 140 ps compared to a σ = 375 ps for the PMT.

B. Low Light Intensity Test

In oder to investigate the energy resolution of the SiPM, we measured the pulse amplitude distribution under low light intensity created by the Optitron unit using a neutral-density

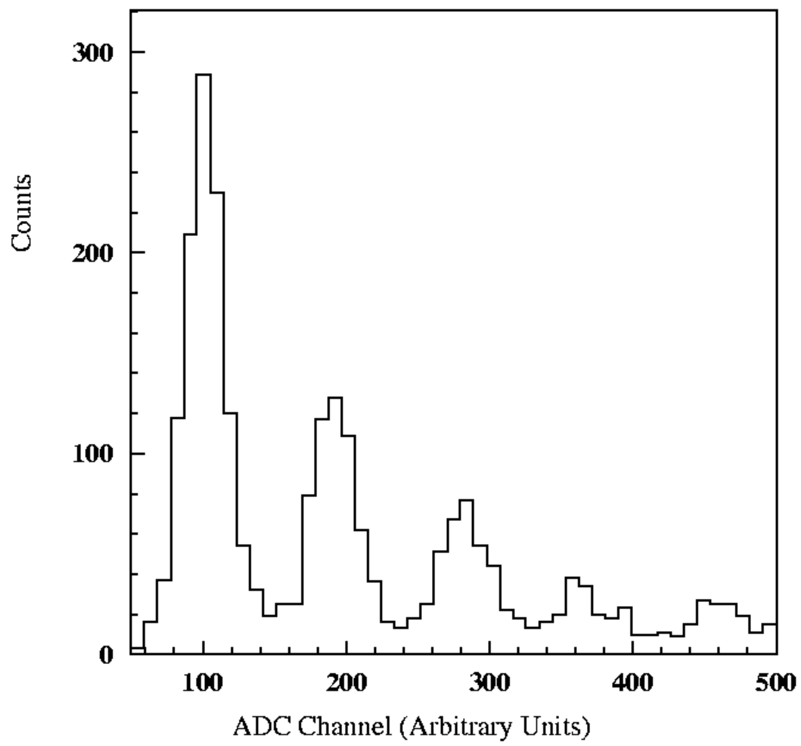

FIG. 3: SiPM pulse height spectrum for low intensity light pulses.

attenuation filter. For this measurement we had to use a fast amplifier (LeCroy 612A) because the amplitude of signals from the SiPM was about 5 - 10 mV. Unfortunately, it was not possible to eliminate completely the noise pick-up from electronic equipment presented in the area, especially the noise originating from the plasma discharge unit. While RF (pick-up) noise was present in all the measurements that utilized the plasma discharge unit, the condition of this noise was negligible compared to the amplitude of SiPM signal output under high flux incident light conditions. However, when only a few pixels generate output, even low amplitude noise contributes to the overall resolution. Nevertheless, the pulse amplitude distribution shown in Fig. 3 exhibits five well separated peaks corresponding to single photon detection and good separation up to five photoelectrons emission. The $2''$ Burle 8575 PMT can not resolve photo-electron peaks.

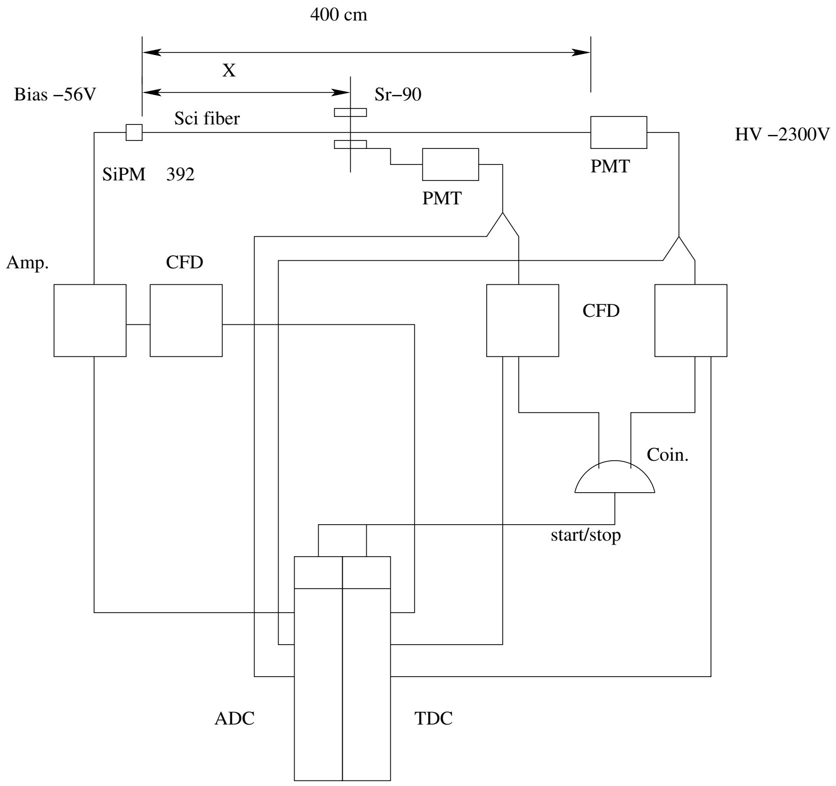

FIG. 4: The electronics diagram of the experimental setup for a 4-m scintillating fiber.

IV. SIPM AS A FRONT-END DETECTOR FOR A 4 M SCINTILLATING FIBER

Having established the intrinsic performance of SiPM devices compared to 2$''$ PMT's, we carried out an experiment to evaluate the performance of the SiPM used as a front-end detector for light signals produced by minimum ionization particles traversing a 4 m long scintillating fiber. The schematic diagram of the experimental setup is shown in Fig.4. A Kurary SCSF-81 single-clad scintillating fiber was used. Scintillating fibers with similar parameters will be used in the barrel calorimeter for GlueX/HallD detector system.

The scintillating fiber was excited using a ^{90}Sr(^{90}Y) beta source with 2280 keV maximal and 935 keV average energy of beta particles. The ionization source had 0.1 μCi activity. The difference in the distributions of ionization energy loss in the scintillating-fiber core, as calculated by a Monte-Carlo simulation for the triggering beta particles and compared to the minimum ionization particles, is only a few percent on average [9].

The Kurary SCSF-81 scintillating fiber has an emission spectrum range of 400 – 550 nm, peaking at 437 nm, with a 2.4 ns scintillation decay time and approximately 3.5 m of

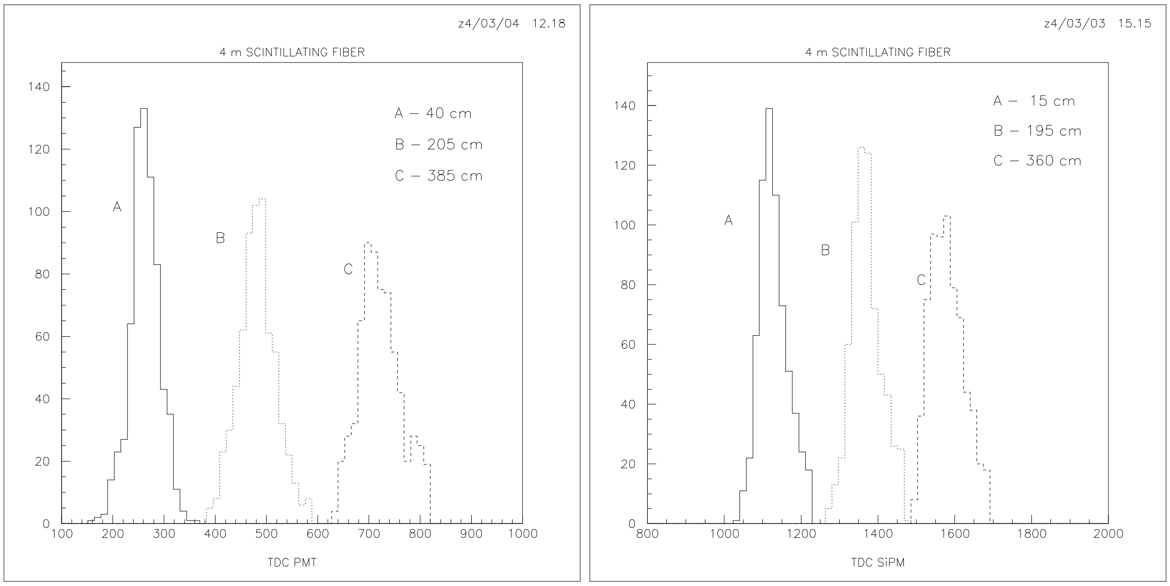

FIG. 5: The timing distributions of pulses obtained from the PMT (left) and the SiPM (right) for different positions of the ionization source. The distances indicated in the graphs were calculated for the TDC PMT from the PMT and for the TDC SiPM from the SiPM.

attenuation length. The scintillating fiber was 1 mm in outer diameter with the cladding thickness being 3 – 7 % the diameter. Both ends of the scintillating fiber were polished to increase the light transmission. A special arrangement was used to preserve the optical connection between the fiber and the sensitive surface of the PMT and the SiPM. One end of the fiber was connected with the SiPM and second one with the PMT. The fiber was in contact with the surface of the PMT window, while it had a 0.3 - 0.5 mm air gap between the end of the fiber and the sensitive surface of the SiPM in order to prevent damage to the SiPM.

The Burle 8575 PMT has a 25 % quantum efficiency at the peak of the Kuraray wavelength while the SiPM's sensitivity for that region is about 15 %. As a result, for the the same light intensity from the scintillating fiber, the SiPM exhibits a photon detection efficiency which is 60% that of the PMT.

An aluminum collimator for beta particles was used to improve the signal to noise ratio. The distance between the ionization source and the fiber was 0.5 cm. A "trigger" detector was placed under the fiber and the ionization source and it registered the beta particles passing through the scintillating fiber. The signals from the PMT's were split into two paths. One, after a delay, was directed to an ADC (LeCroy 2249A) for amplitude spectrum

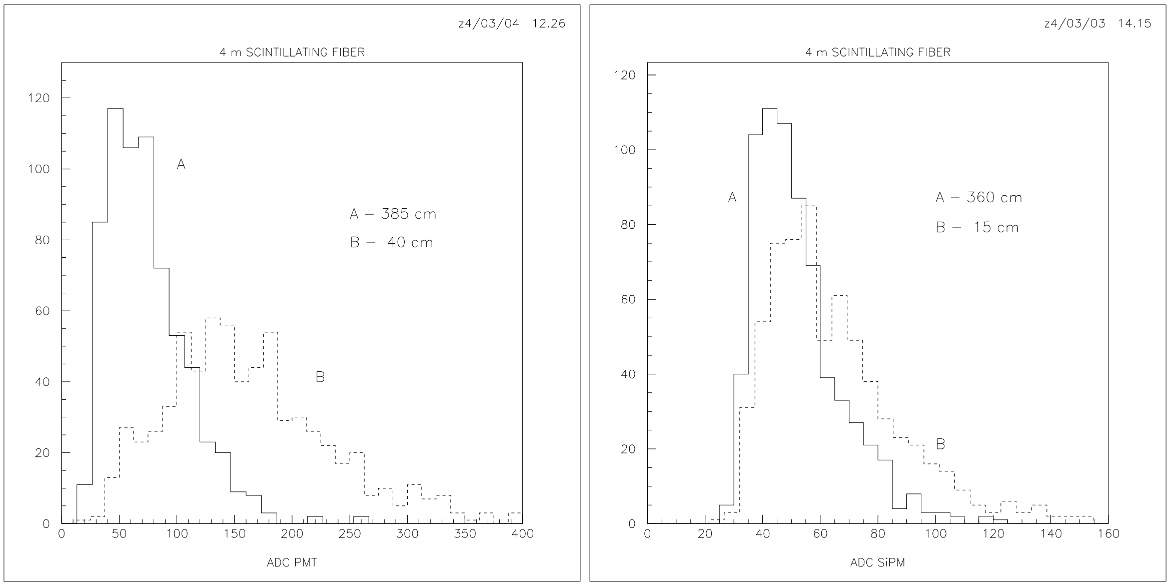

FIG. 6: The pulse height spectra of the output signals from the PMT (left) and the SiPM (right) produced by the triggering beta particles in a scintillating fiber. Spectrum 'A' ('B') corresponds to maximal (minimal) distance from an ionization source.

measurement. The second path passed through a constant fraction discriminator (Ortec CFD 455) set to minimize the "walk" correction of the signals from the PMT's. The coincidence (LeCroy465) between the two PMT's signals created a "start" signal for the Camac ADC/TDC units. The integration time window for the TDC unit (LeCroy TDC 2228A) was set to 120 ns.

The signal from the SiPM was amplified by a fast 12-channel amplifier (LeCroy 612A). The LeCroy 612A has a 200 MHz bandwidth, fast rise time, DC-coupling, 1 mV stability at the output, 0.1 % integral linearity and insures a faithful reproduction of signal shape after amplification. The gain factor was set to 10. One output pulse of the amplifier was digitized by a ADC 2249A unit. The second was through to a CFD 455 to a TDC unit.

The TDC/ADC spectra were accumulated and analyzed for different positions of the ionization source across the 4-m scintillating fiber. The distance was measured from the SiPM in all measurements. The PAW++ [10] software was used to analyze the ADC/TDC spectra. The measured spectra generated from the SiPM and the PMT - for different ionization source positions - are shown in Fig.5 and Fig.6 for the TDC and the ADC spectra, respectively. The TDC spectra (Fig.5) for the PMT and the SiPM have identical shapes. As the ionization source moves away from the sensitive surface of the PMT or the SiPM,

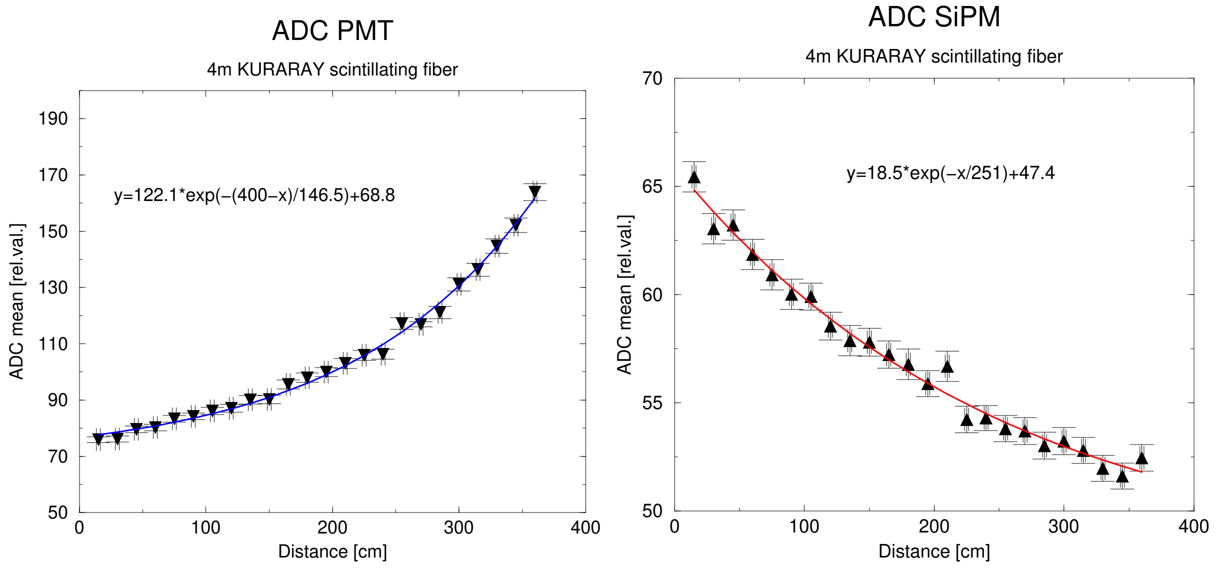

FIG. 7: The dependence of the scintillation light yield with distance from the SiPM is shown for the PMT (left) and the SiPM (right).

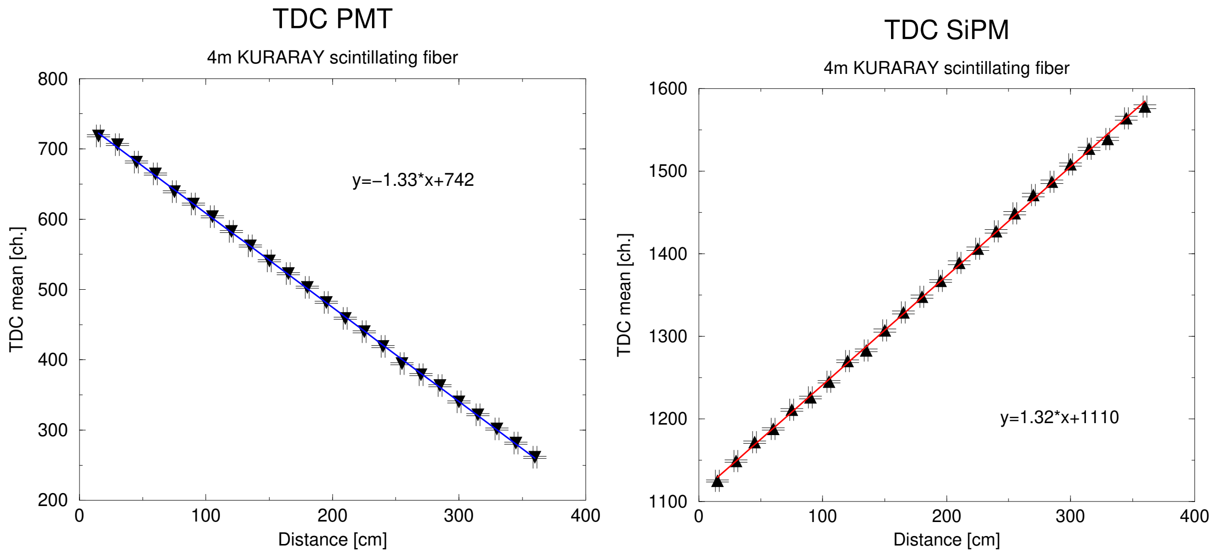

FIG. 8: The time propagation of the scintillation light along the fiber. The left (right) graph corresponds to the PMT (SiPM) experimental data.

a monotonic shift of the peak position was observed. The TDC spectra were fit with a Gaussian curve and the mean parameter and the σ of the obtained spectra were used in the analysis that follows.

The ADC spectra (Fig.6) for the PMT and the SiPM correspond to the physical process of a light attenuation as a function of distance from the front-end detector to the position of the ionization source. The mean values of the distributions were used in the calculation of the attenuation length and are plotted in Fig.7.

The experimental data were fit with an exponential curve:

y=I·exp(-x/L),

where I is the amount of light produced at the interaction point, L is the attenuation length and x is the distance to the ionization source.

The ratios of the mean values for the two identical positions of an ionization source are larger for the PMT in comparison with the SiPM. As a result, two different attenuation lengths were obtained for the same fiber (L_{SiPM}=251 cm and L_{PMT}=146 cm for the SiPM and the PMT data, respectively). The reason for this is the difference in the spectral sensitivity of these two devices. The SiPM is more sensitive to longer λ compared to the PMT and, at the same time, the transmission loss for the Kuraray fiber is lower for the SiPM region of sensitivity in comparison with the same for the PMT. As result, the SiPM experimental data give a larger value of the attenuation length in comparison with the PMT data.

The TDC peak location (the mean value of the Gaussian fit) was plotted versus the distance from the front-end detector and is displayed in Fig.8. The experimental data were fit with a linear fit. The slopes of the linear fit curves for the SiPM and the PMT agree with each other within the error of measurement, and are equal to 1.32±0.01 ch/cm and 1.33±0.01 ch/cm for the SiPM and the PMT experimental data, respectively. The TDC conversion factor was 47 ps/ch. The calculation of the velocity of light propagation gives v=(1.60±0.03)·10^8 m/sec that agreen with the Kuraray fiber specifications sheet.

The timing resolution is an important factor in the determination of the position of a particle traversing the fiber and was evaluated by measuring the time distribution of the signal by the front-end detectors, fit by a Gaussian curve. The timing resolution is presented in Fig.9 as a function of the distance of the ionization source from each front-end detector. The start signal was provided by the coincidence unit between the trigger detector and the front-end PMT. The data presented in Fig.9. have not been corrected for the time jitter of the trigger detector. Additionally, quoted timing resolution for the SiPM combines the

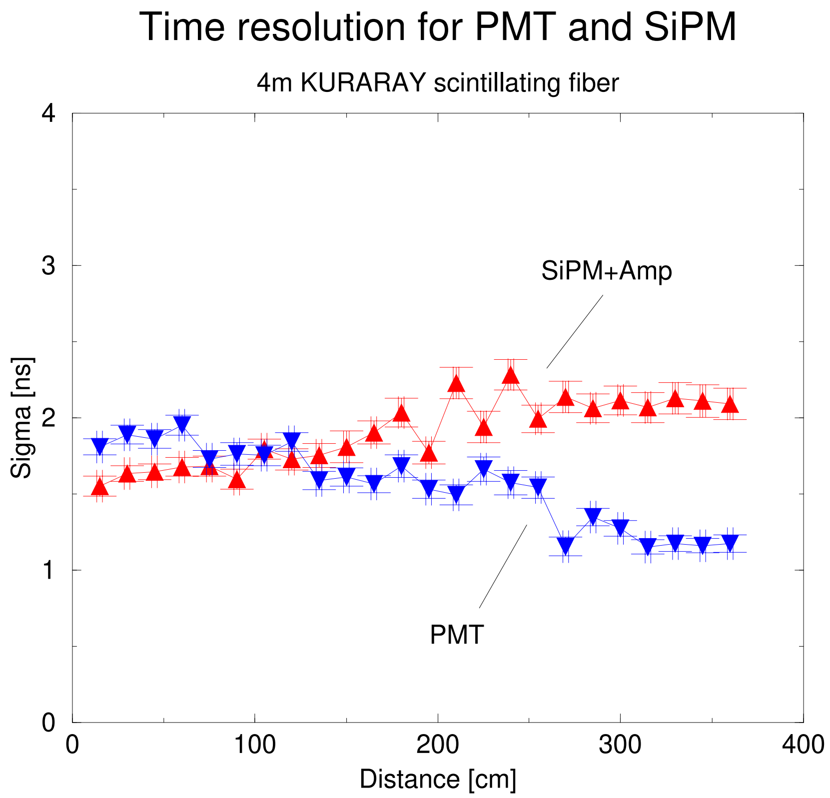

FIG. 9: The timing resolution as a function of the distance from the SiPM detector.

intrinsic SiPM resolution plus the jitter connected with the LeCroy 612 amplifier.

The best values of sigma were 1.5 ns and 1.1 ns for the SiPM and the PMT, respectively, corresponding to the minimal distance between the ionization source and the front end-detector. The sigma monotonically increases as the ionization source moves away from the front-end detector.

The timing resolution is very sensitive to the number of detected photoelectrons. The average number of photoelectrons detected by the SiPM was about five for the 15 cm position of ionization source from the SiPM. The ADC spectrum from the PMT for a minimal distance from an ionization source was accumulated from the large number of photoelectrons in comparison with the SiPM. Nevertheless, the timing resolutions for the SiPM and for the PMT timing spectra are comparable.

V. CONCLUSIONS

The properties of the SiPM working in Geiger limited mode have been measured and compared with a standard photomultiplier tube. The measurement with the nitrogen laser shows that the SiPM has better time and energy resolutions in comparison to the 2″ Burle PMT under high light intensity. To evaluate the possibility of using the SiPM as a front-end detector for a BCAL calorimeter readout system, we measured the ADC/TDC spectra from the SiPM for 4 m scintillating fiber irradiated by ^{90}Sr beta source. The result of investigations indicates the SiPM satisfies the requirements for a BCAL calorimeter.

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