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Application of the silicon photomultipliers for detectors in the GlueX experiment

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Abstract

The GlueX detector in Hall D at Jefferson Lab [1]is instrumented with about 5000 Silicon Photomultipliers (SiPM) manufactured by Hamamatsu Corporation [2]. These photo sensors have properties similar to conventional photomultipliers but can be operated at high magnetic fields. Silicon photomultipliers with a sensitive area of 3x3 mm^2 are used to detect light from the following GlueX scintillator detectors: the tagger microscope, pair spectrometer, and start counter. Arrays of 4x4 SiPMs sensors were chosen for the instrumentation of the barrel electromagnetic calorimeter. The tagger microscope must operate at high rates (up to 2.5 MHz) and provide time measurements with a resolution better than 0.3 ns. The paper will describe some results of the characterization of SiPMs for various GlueX sub-detectors.

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Keywords: *Detectors; Silicon Photomultipliers;GlueX experiment.*

1. Introduction

The Silicon Photomultiplier (SiPM) is a novel solid state photon counting device [3]. It has many favorable features such as: low operation bias voltage below 100 V, high gain of approximately 10^6, compactness, insensitivity to magnetic fields, good time resolution, high photon detection efficiency ranging between 20-40 %. SiPM is an array avalanche photodiodes (APD), which are operated in a Geiger-mode and are connected through a passive

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quenching resistor. Each APD has a size varying from 25×25 μm^2 to 100×100 μm^2 (the so-called pixel size) and is capable of detecting photons independently. All pixels in the array are connected electrically in parallel to a common output. The output pulse amplitude is proportional to the number of pixels fired, i.e., to the number of detected photons. SiPM are used in several sub-detectors of the GlueX experiment. The GlueX experiment and application of SiPMs in various sub-detectors will be described in Section 2. Measurement results of some SiPM characteristics will be presented in Section 3.

2. Application of SiPMs in GlueX experiment

2.1. The GlueX experiment

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab provides a unique high-intensity beam of linearly polarized photons produced using a bremsstrahlung technique [4]. The photon beam will be used by the new experiment GlueX constructed in the experimental Hall D [1]. The main goal of the GlueX experiment is to provide critical data, that will help to quantitatively understand confinement of quarks and gluons in quantum chromodynamics (QCD). Confinement is a unique property of the QCD associated with a gluonic field responsible for binding quarks in hadrons. Hybrid mesons with exotic quantum numbers (J^{PC}) provide a unique opportunity for testing QCD in the confinement regime since these mesons explicitly manifest gluonic degrees of freedom. Photoproduction is expected to be particularly effective in producing exotic hybrids.

2.2. Tagger Microscope

The photon beam is produced by a 12 GeV electron beam incident on a thin (20μm) diamond radiator. Coherent radiation from the diamond crystal lattice results in sharp monochromatic peaks in the photon energy spectrum. The photon energy range of interest for GlueX (corresponding to the largest coherent peak) is between 8.4 GeV and 9.1 GeV. The photon energy in this region will be determined by fine resolution hodoscope (tagger "microscope") with an accuracy of about 0.1% by measuring the energy of the electron after radiation. The microscope is composed of a two-dimensional array 100x5 square scintillating fibers with a cross section of 1 mm^2, as shown in Fig. 1. Electrons from the spectrometer travel parallel to the axis of the fibers. Clear fibers attached in the back end of the scintillating fibers transport the light from the scintillator fibers to SiPMs, located in a region with low radiation. SiPMs (Hamamatsu MPPC S10931-050P [2]) with a sensitive area of 3 x 3 mm^{2}and a pixel size of 50 μm are used. The average amount of light collected from scintillators corresponds to about 200 pixels fired in a SiPM. Photo sensors will be operated at a relatively large rate of about 2.5 MHz and should provide time measurements with a resolution better than 300 ps.

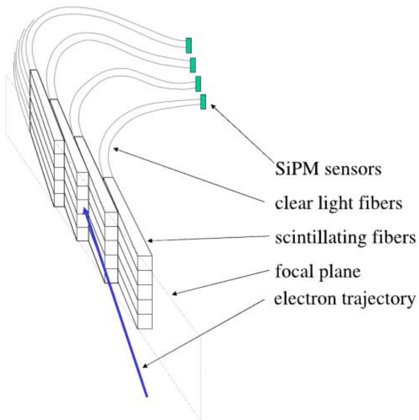

Fig.1. Conceptual design of a segment of the tagger microscope, showing the two dimensional array of scintillating fibers and the clear fiber light guides, that couple the light to the silicon photomultipliers.

2.3. Pair spectrometer hodoscope

One of the key components of the Hall-D photon beam line is the pair spectrometer [5], which is installed after the photon collimator in front of the GlueX detector. The spectrometer will measure the energy of a beam photon by detecting an $e^{\pm}$ pair produced by the photon in a thin converter. The main purpose of the spectrometer is to measure the spectrum of the collimated photon beam and determine the fraction of linearly polarized photons in the coherent peak energy region. Electron-positron pairs are created by beam photons inside a thin converter with a typical thickness of ~ 10^{-3} radiation length. The produced leptons are deflected in a dipole magnet and registered in two layers of scintillator detectors: a high-granularity hodoscope and a set of coarse counters. The detectors are organized into two arms positioned symmetrically with respect to the photon beamline. Each high-granularity hodoscope consists of 145 thin scintillator tiles (1×10×30 $mm^3$and 2×10×30 mm^3) stacked together. The light from each tile is collected by means of a 1×1 mm^2 wavelength shifting fibers. Each fiber is coupled to a Hamamatsu SiPM (MPPC S10931-050P). The average amount of light seen by a SiPM corresponds to about 50 – 60 fired pixels. The read out board with 145 SiPMs installed is shown on Fig. 2.

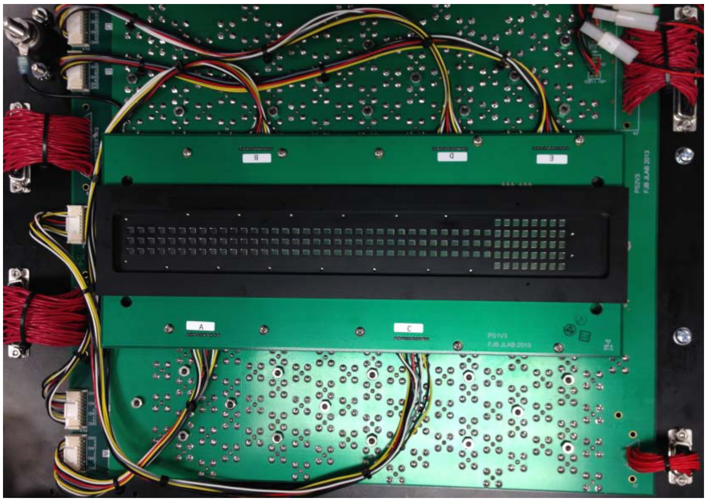

Fig.2. The high-granularity pair spectrometer read-out electronics board with SiPMs installed on it.

2.4. Start Counter

Collimated beam photons are subsequently sent to the GlueX liquid hydrogen target surrounded by the start counter (ST) and positioned inside the GlueX superconducting solenoid magnet. The ST consists of a cylindrical array of scintillator pads. The purpose of the GlueX start counter is (in coincidence with the tagger) to identify the electron beam bucket where the interaction occurred. Light from each pad is detected by 3 SiPMs attached to one side of the pad. SiPMs of the same type as for the tagger microscope and the pair spectrometer hodoscope are used. The operation rate of the ST is about 200 kHz per pad. The detector time resolution is about 300 – 500 ps.

2.5. Barrel calorimeter

Another GlueX sub-detector, which is instrumented with SiPMs is the barrel calorimeter (BCAL) [6]. The BCAL consists of 48 identical modules built using lead sheets with grooves and scintillating fibers positioned inside them. The module is read out from both sides by 40 SiPM photodetectors as shown in Fig. 3. The photodetectors are compact and tolerant to a magnetic field above 0.5 T. Each photodetector is an array of 4x4 custom silicon photomultipliers (3×3 mm^2 each) manufactured by Hamamatsu Corporation (S12045 (X)), which size is 1.2×1.2

cm^2.Several photodetector types including fine mesh PMTs were considered for the BCAL instrumentation, but SiPMs were found to be the most appropriate solution.

Fig.3. Photon energy spectrum measured with the PS hodoscope during the first commissioning run with a diamond radiator.

Silicon photomultipliers manufactured by Hamamatsu Corporation (MPPC S10931-050P) with a sensitive area of 3x3 mm^2 are used to detect light from the tagger microscope, pair spectrometer, and start counter. Arrays of 4x4 custom silicon photomultiplier manufactured by Hamamatsu Corporation (S12045 (X)) were chosen for the instrumentation of the barrel electromagnetic calorimeter.

3. SiPM timing measurements

3.1. Timing resolution

SiPMs are known to have extremely good time resolution, even for small amount of light corresponding to a single-pixel response [7]. The rise time of the light pulse and readout electronics can significantly affect timing characteristics of the detector. We measured the time resolution of Hamamatsu SiPMs with a sensitive area 3x3 mm^2 and pixel size of 50 microns (MPPC S10362-33-050C) for various numbers of fired pixels and operation rate. Measurements were made using a picosecond laser pulser and light produced by an LED with total pulse width of 8 ns. In the first case, the time resolution is limited by readout electronics. For studies with an LED, the main contribution to the time resolution comes from the rise time of the light pulse of ~ 3ns. The rise time is comparable with the light collection time from a scintillator using transparent fibers or wavelength shifter fiber (WLS). We also measured the dependence of the time resolution on the number of fired pixels for the SiPM array at a room temperature and at 5 ^{0}C. These SiPMs are most sensitive in a "blue" light (≈ 470 nm), which is consistent with the spectrum of the emitted light from scintillator EJ – 212 [8].

SiPM time characteristics were studied using a pulse generator (HP 8116, 8 ns pulse width), which drove a fast blue light emitting diode (LED) and a trigger for data readout, and a two identical SiPMs, located equidistant from the light source and connected to a custom made broadband fast preamplifier. The amplified signals were sent to a 12-bit ADC (fADC250) [9] and through discriminator CFD Ortec 935 to a 25-ps TDC Caen VX 1290. Using two identical SiPMs reduces the impact of the instability of the LED pulse and the systematic effects from the electronics. Stability of the LED pulse as a function of frequency and signal amplitude were measured using a calibrated photosensor. Results showed that the pulse from the LED was stable up to 10 MHz.

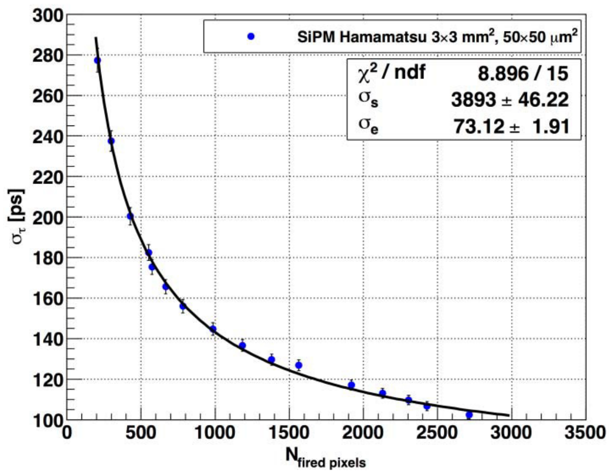

Fig. 4. Timing resolution of the MPPC S10362-33-050Cas a function of the number of fired pixels measured by the simulation of the signal from fast scintillator.

Charged Calibration of each SiPM was carried out using a low-intensity LED light. The amplitude of the SiPM signal was digitized using a flash ADC operated at a sampling rate of 250 MHz. Digitized signal pulse was summed in a 40 ns window. The single pixel ADC response was determined from a ADC spectrum. Time resolution was determined using a time difference between two SiPMs as:

$$\sigma = \frac{\sigma_{t_1 - t_2}}{\sqrt{2}} \tag{1}$$

The dependence of the time resolution of the SiPM S10362-33-050Con the number of fired pixels measured by the LED is shown on Fig. 4. This dependence is fitted using the following function:

$$\sigma_\tau = \sqrt{\frac{\sigma_s^2}{N_{f.pix}} + \sigma_e^2} \tag{2}$$

where $N_{f.pix}$ is the number of pixels fired in the SiPM, σ_s and σ_e are two free parameters in the fit. σ_s is associated with statistics of photoelectrons, and σ_e is determined by electronics. The timing resolution is found to be less than 300 ps for 200 fired pixels, which is expected to correspond to the amount of light seen by the tagger microscope.

The same measurements were done with the Hamamatsu PLP 10 laser. The laser pulse width is about 60 ps. Time resolution as a function of the number of fired pixels in MPPC S10362-33-050C and MPPC S12045 (X) at room and working temperatures is presented on Fig. 5. The results show:

1. The time resolution of the array is worse due to a substantial increase of the dark noise by combining of 16 SiPMs. For the same reason, the dependence of the time resolution on the temperature is stronger for a fewer number of fired pixels.

2. The time resolution is found to be on the level of 20 – 30 ps starting from ~ 150 fired pixels for MPPC S10362-33-050Candfrom ~ 300 fired pixels for MPPC S12045 (X). It is determined by readout electronics and the time resolution of the SiPM itself.

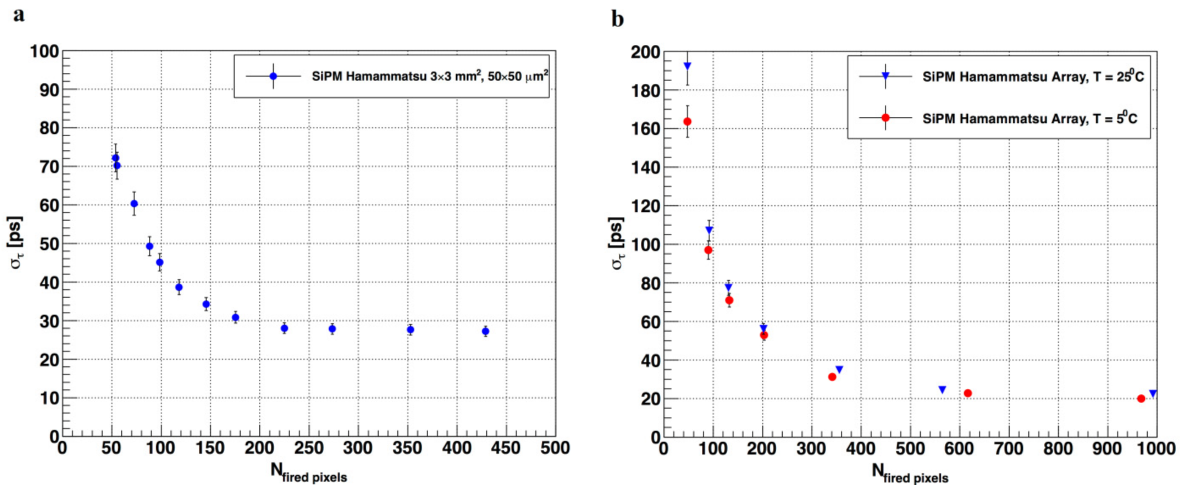

Fig. 5.Timing resolution as a function of the number of fired pixels measured by using Hamamatsu PLPQ 10 laser pulser: (a) MPPC S10362-33-050C; (b) MPPC S12045 (X) at 25 ^{0}C (triangles) and at working temperature of 5 ^{0}C (circles).

Time resolution of the MPPC S10362-33-050C does not substantially change until ~ 2.5 MHz (Fig. 6), which is the estimated nominal operation rate of the tagger microscope.

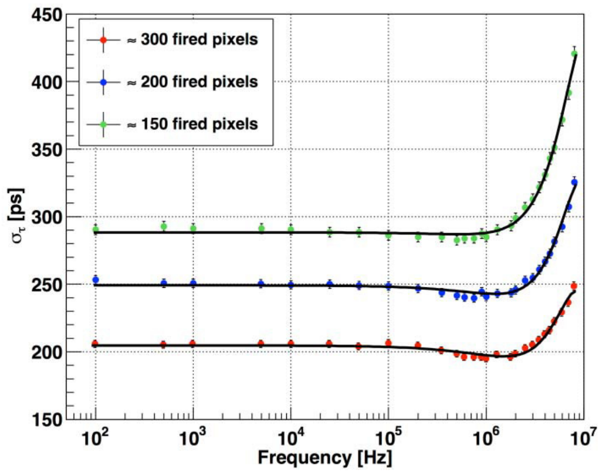

Fig. 6. Timing resolution of the MPPC S10362-33-050C as a function of load rate measured by the simulation of the signal from fast scintillator.

3.2. Pixel recovery time

Rectangular pulse from a bipolar pulse generator (BK Precision 4071A) was used to synchronize two identical pulse generators (HP-8116). These generators were used to fire two blue light emitting diodes and allowed to change the amount of light emitted by the LEDs. The first LED operated at high SiPM load and fired about 80 - 90% of the whole number of pixels. The second LED fired after the first one and provided a flash with a relatively small light intensity. We measured the SiPM signal amplitude produced by the second LED for various delays between the two flashes and the amount of light. It allows us to estimate the recovery time of a SiPM, which was measured at a point where the SiPM amplitude from the second LED drops by 20%. The amplitude of the second LED as a function of the delay for several numbers of fired pixels is shown on Fig. 7. The typical MPPC S10362-33-050C pixel recovery time is τ = 35 – 40 ns.

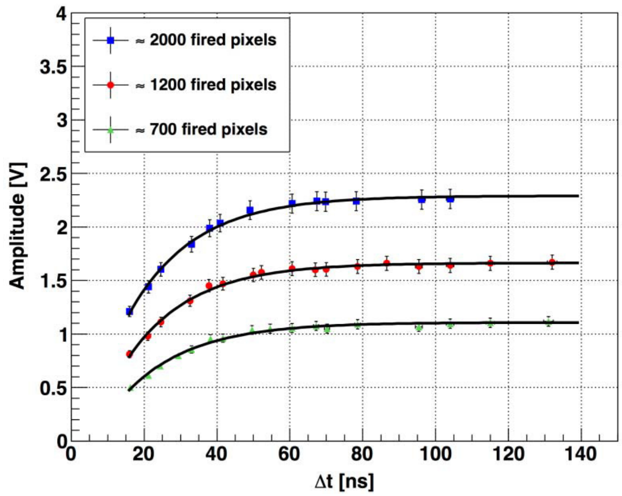

Fig. 7. Pixel recovery time of the MPPC S10362-33-050C.

4. Conclusion

The GlueX detector in Hall D at Jefferson Lab is instrumented with about 5000 SiPMs manufactured by Hamamatsu Corporation. Silicon photomultipliers with a sensitive area of 3x3 mm^2 are used to detect light from the tagger microscope, pair spectrometer, and start counter. Time resolution of SiPMs measured using an LED (by simulating signals from a fast scintillator) was found to be less than 300 ps for a SiPM operated at a rate up to 2.5 MHz. Arrays of 4x4 SiPMs are used for light detection for the barrel electromagnetic calorimeter. Time resolution measured for the SiPM 4x4 array was found to be slightly worse than that for the individual 3x3 mm^2 SiPM sensor; the 30 ps resolution was observed for 300 and 150 pixels fired in the array and the single SiPM (MPPC S10362-33-050C), respectively.

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