PHOTODETECTOR TIMING RESEARCH AT FERMILAB*

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(Received January 31, 2011)

We describe here the outlines of research undertaken by Fermilab into timing characteristics of photodetectors. We describe our experimental method and give benchtop results on the timing resolution of micro-channel plate photomultipliers (MCP-PMT) and silicon photomultipliers (SiPM). In addition, we describe results of various configurations of these detectors, along with quartz radiators, in particle test beams at Fermilab. Results for timing of scintillator light using the DRS4 high speed digitizer are also presented.

DOI:10.5506/APhysPolBSupp.4.29

PACS numbers: 42.79.Pw, 07.77 Ka, 29.40.Ka, 85.60.Gz

1. Introduction

A new generation of photodetectors with small feature size can give significantly better timing performance. One such photodetector is the microchannel plate PMT (MCP-PMT), with a parallel array of thin microtubules containing an emissive layer for electron amplification. The pore size is typically on the order of 10 microns and the distance from photocathode to the first amplification stage is only a few mm. The other new photodetector is the solid state silicon photomultiplier (SiPM), which is a device with an array of tiny (order 50 μm) Geiger mode avalanche pixels, whose count above

* Presented at the Workshop on Timing Detectors, Kraków, Poland, November 29–December 1, 2010.

background is equal to the number of photons hitting the device. Both of these devices can give superb timing resolution, on the order of 20 ps (Gaussian fit σ) or better and Fermilab has been involved for the last several years in systematic studies of them.

2. Benchtop measurements

We created a test setup at the Silicon Detector Facility at Fermilab to study photodetector timing at the few ps level. This setup has been described previously [1]. It consists of two paths of signals, each path being split with a high bandwidth splitter, into a pulse height measurement and an Ortec 9327 constant fraction discriminator input. The two discriminator signals are fed into an Ortec 567 time-to-analog convertor, whose analog output was subsequently measured by a 14 bit Ortec AD114 ADC. This system has demonstrated 3 ps intrinsic time resolution consistently. One way of using this setup was to use a PiLas fast laser pulse, or an LED pulse, illuminating the device to be measured. Another way is to use two similar devices and measure the time difference for identical light pulses into each device. This setup could be transferred to the Fermilab Test Beam Facility for our measurements with beam.

We found that the MCP-PMT Photek PMT210 and PMT240 gave excellent timing resolution using our test bench [2]. (We subsequently used the PMT240 as a reference in the test beam measurements, since they gave a better timing signal for the particles than any signal from the accelerator.) Each device contains two microchannel plates, in a chevron pattern. The PMT240 has a 40 mm circular aperture, while the PMT210 has a 10 mm aperture. The PMT240 has a Single Photon Time Resolution (SPTR) specification of at most 100 ps, a parameter that we investigated more precisely. The PMT240 was mounted inside the setup dark box and illuminated by 405 nm PiLas laser light. We obtained data for a 1 mm diameter spot in the center of the photocathode, and at a radius of 18 mm, close to the edge. We found that there is no spatial dependence of the SPTR. The photocathode is isochronous within about 5 ps, according to this study.

The number of photons impinging on the detectors was changed by optical filters applied to the output light of the PiLas laser head. We used attenuators between the PMT240 output and the CFD 9327 input to maintain the signal in the best timing range of the 9327 (approximately 40 mV). We calculated the number of photoelectrons from the Gaussian width of the pulse height spectra and verified from the single photoelectron amplitude that this approach gives 10% accuracy. The SPTR for the PMT240 was measured to be 35 ps. For larger numbers of photons, the time resolution of the PMT240 improves as the inverse square root of the number of photoelectrons. However, the overall level for the resolution with larger numbers of photoelectrons extrapolates to be about twice as worse as would be expected from the SPTR. We do not know the reason for the discrepancy between the single and multiple photoelectron results. We studied the Photek PMT210 timing properties in the same setup. As would be expected with the smaller diameter photocathode, the SPTR was found to be better than that of the PMT240 with an SPTR of 27 ps.

We also studied silicon photomultiplier (SiPM) devices for their timing resolution, using the same setup. We have found the SPTR for the Hamamatsu MPPC with 3×3 mm^2 of sensitive area to be 120–150 ps, (with an overvoltage up to 2.2 V) [3]. We also tested SiPMs produced by STMicroelectronics (STM). For these STM devices (3.5×3.5 mm^2 sensitive area) we measured about the same SPTR with an overvoltage of 5 V.

We tested the SiPM response to two different wavelengths of light (405 and 635 nm), using the PiLas laser system. We found distinctly different dependencies on the wavelength of the response from the two types of SiPM. For the STM devices the red light gave consistently poorer time resolution than the blue light. The opposite case exists for the Hammamatsu devices. We speculate that if the $n+$ side of the silicon faces to the light the SPTR is better for the blue light, and if the $p+$ side of the silicon faces to the light the SPTR is better for the red light. This effect is related to the photon absorption length in silicon, the shape and location of the high field region, and the type of carriers in each case. We gave a simple explanation of this phenomenon in a previous study [4].

3. Test beam measurements

We used the Test Beam Facility in the Meson Detector Building at Fermilab, with 120 GeV/c protons from the Main Injector accelerator, as well as some tests with lower momentum secondary beams. We used an identical setup as in the bench measurements, except that we formed three separate time difference measurements, using three different device inputs. In this fashion we could disentangle the contributions from each device. The trigger counter was a single 2×2 mm^2 scintillation counter, 16 mm thick, viewed by two PMTs in coincidence. An octagonal scintillation counter 10 cm across with a central 7 mm diameter hole was used as a veto counter to reject events with particles outside the study area, which may indicate upstream interactions. All the detectors were in a dark box lined with copper sheet for RF shielding. For some tests the third counter was outside the dark box.

We had two periods of study in the beam line, in May 2009 and March 2010. We first describe the Photek MCP-PMT results obtained in 2009. We arranged the counters inside the dark box so that 120 GeV/c protons passed at normal incidence through the face of all three MCP-PMTs in sequence. The input windows of the photodetectors (6 mm for the Photek 210 and 9 mm for the Photek 240) thus served as Cherenkov radiators. Calculations indicate that we would expect 30–40 photoelectrons for the Photek 210, while we expect 70–80 photoelectrons for the Photek 240. We obtained 13 ps resolution for passing protons in the PMT210s and 8 ps for the PMT240 from the resolution unfolding.

We then attached 6×6 mm^2 quartz bars, of various lengths, to the PMT210 tubes. We arrayed these counters at the Cerenkov angle for quartz (48 degrees) so that there would be minimal reflections occurring for light generated by a passing particle. Note that the configuration of the counters on the same side of the beam eliminates the time spread resulting from the beam width, while arraying the counters on opposite sides of the beam will give a mean-time measurement. These measurements allowed us to define the time resolution of each counter and to choose the best option for an actual particle species time of flight measurement. The PMT240 was used as a stop counter 8.7 m downstream of the PMT210 start counters, with quartz bars. We used the best front end configuration with the 9327 CFDs placed close to the PMT210s. The TOF spectra obtained with positively charged particles of momentum 4, 6 and 8 GeV/c clearly shows peaks coming from protons in the beam. The dominant fast peak is due to positrons and pions. The measured TOF spectrum fit Gaussian σ for the fast peak was 24 ps, which includes a contribution from the pion TOF itself.

We now describe the results obtained in the second test beam run (March 2010). We obtained a second PMT240, and we installed the two PMT240s with an array of quartz bars — three identical rows of five bars. Each bar was coupled to the PMT window with optical grease, with a spring pressure. Since the PMT240s are isochronous across their photocathode, all the light generated in the multiple bars will contribute to the same timing measurement. With the two detectors mounted on opposite sides of the beam we measured 11 ps resolution for this arrangement, using mean timing analysis. Another true TOF measurement was done with 7.1 m between the start and stop Photek 240 counters, with normal incidence and with Cherenkov light produced in their windows. The beam momentum was 8 GeV/c. The measured TOF time difference between particles had a resolution of 14 ps, with clear separation of the proton peak. This is comparable to the fastest beam line measurements previously made [5].

4. Fast digitization techniques

We have begun investigations into timing properties of crystals attached to SiPM detectors, using fast digitization techniques. Our setup consists of 2 SiPms with optically attached crystals inside of Pomona boxes. A Keithley

2410 power supply was used to bias these SiPMs. The devices were placed on either side of a Na-22 positron source. The signals from the SiPMs were split into 2 halves, with one of the signals participating in a coincidence trigger, while the other half was input into the digitizing module named DRS4, obtained from the Paul Scherrer Institute [6]. We used the version of the DRS4 with 4 input channels, a sampling rate of 5 GS/s and an individual channel depth of 1024. Sometimes we used an Ortec V120C to amplify the SiPm signals to fit the DRS4 dynamic range. We measured time and pulse height distributions with the following variables:

1. Two types of SiPMs: We studied devices from STM and from Hamamatsu.
2. LYSO Crystals of different size.
3. Using a clipping capacitance circuit and without it.
4. Radioactive sources Co-60 or Na-22.

The STM device we used had a sensitive area of 3.5×3.5 mm^2, with 4,900 pixels of size 50×50 μ^2, photon detection efficiency (PDE) of about 30% for blue light, and an overvoltage at 5 V. The Hamamatsu device sensitive area is 3×3 mm^2, with 3,600 pixels of size 50×50 μ^2, PDE is about 45% for blue light, and an overvoltage is up to 2.5 V. We attached LYSO crystals whose sizes were $3 \times 3 \times 15$ mm^3, $3 \times 3 \times 10$ mm^3, $3 \times 3 \times 20$ mm^3 and $2 \times 2 \times 7$ mm^3. We found the shape of the signals does not depend on the crystal size used when under source irradiation. The shape of the signals was strongly dependent on whether or not we used a clipping capacitance (described in Ref. [1]).

We started data analysis with fitting to the leading edge of the signals by a simple straight line. The point at half maximum of the signal amplitude was detected. A study of laser light indicated that 8 ps resolution could be achieved with this method. Another analysis was performed for the points where the straight line crossed the signal base line. This approach was applied both to data obtained with the PiLas and radioactive source. As a result we found that the natural shape of the signals leading edge is far from a straight line especially for data with the radioactive source and without any shaping of signals. Even for short signals we observed different slopes along the leading edge. That is why a pulse function approach was introduced. A simple model of a SiPM as charging/discharging capacitance was taken as a first approximation to the pulse function. Comparison of the real signal shape with the function showed the function should be smeared by convoluting it with a Gaussian distribution. We got a significant improvement of the electrical time resolution (4 ps instead of 8 ps) by applying the function to the PiLas data. To analyze data obtained with a radioactive source the pulse function was convoluted with the LYSO crystal decay time T. We obtained good fitting of the function to the real SiPMs signals for both PiLas and radioactive source data. Both single photoelectron SiPm signal and crystal light pulses have very sharp leading edge and much slower falling tails. Shortening of the SiPM signal with clipping capacitance allowed us to get a sharp leading edge and we have obtained 150 ps as our best effort so far. We consider this study as the first step for design and production of a TOF-PET module prototype.

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