Study of timing performance of Silicon Photomultiplier and application for a Cherenkov detector

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Abstract

Silicon photomultipliers are very versatile photo detectors due to their high photon detection efficiency, fast response, single photon counting capability, high amplification, and their insensitivity to magnetic fields. At our institute we are studying the performance of these photo detectors at various operating conditions. On the basis of the experience in the laboratory we built a prototype of a timing Cherenkov detector consisting of a quartz radiator with two $3 \times 3$ mm$^2$ MPPCs S10362-33-100C from Hamamatsu Photonics as photodetectors. The MPPC sensors were operated with Peltier cooling to minimize thermal noise and to avoid gain drifts. The test measurements at the DAφNE Beam-Test Facility (BTF) at the Laboratori Nazionali di Frascati (LNF) with pulsed 490 MeV electrons and the results on timing performance with Cherenkov photons are presented.

Key words: Silicon photomultiplier, Cherenkov detector, Time resolution

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1. Introduction

A Silicon Photomultiplier (SiPM), also sometimes referred to as pixelized photon detector (PPD) is a novel semiconductor photon detector. It consists of a large matrix of avalanche photodiodes (APD), operated in limited Geiger mode. It has an intrinsic gain for single photoelectrons of typically $10^6$, which is comparable to that of a vacuum photomultiplier tube (PMT), and considerably higher than that of an APD operated in linear mode [1][2][3]. Devices from Hamamatsu Photonics [4] feature typical gain values from $2.5 \cdot 10^5$ to several million, depending on the specific pixel number. The photo detection efficiency is peaked at around 440 nm. Together with its compact size (typical sensitive area of 1 to 10 mm$^2$) it makes them ideal for scintillating fiber readout [2][8]. Insensitivity of the SiPM to a magnetic field is a big advantage compared to the PMT. The SiPM response, gain, cross-talk, and noise frequency do not change in the magnetic field within the measurement accuracy, allowing operation even in high magnetic fields and so a much more compact design of detectors can be achieved [1][9].

SiPMs are also suited for the readout of Cherenkov detectors [5][6]. By combining the fast photon generation from the Cherenkov process with the high photo-detection efficiency, sensitivity to low numbers of photons, and good timing performance of the device [7], such a counter could be used as a beamline TOF-start counter as needed in high-energy physics experiments. Due to its compactness and the possibility to operate it in magnetic fields it could be a valuable alternative to the commonly used scintillating detectors with PMT readout or CVD Diamond detectors [1][11].

In this paper we present results of an in-beam test of a prototype Cherenkov detector which uses SiPMs as read-out device. We exposed the detector to an electron/positron beam ($e^+/e^-$) of ~ 490 MeV at the DAφNE Beam-Test Facility (BTF) at the Laboratori Nazionali di Frascati (LNF) and measured the light outcome as well as the timing resolution of this prototype device.

2. Prototype Cherenkov detector

The prototype Cherenkov detector is displayed in figure[1] It consists of a slab-like radiator of 3 mm thickness and 50 mm length. The central part has a cross section of $10 \times 3$ mm$^2$. On both ends it narrows down to a quadratic surface of $3 \times 3$ mm$^2$. The radiator is made of quartz.

The Cherenkov photons produced by a particle traversing the radiator are supposed to be totally reflected on the internal surfaces of the radiator and to be guided to its both ends. In order to reduce the losses due to imperfect reflection the radiator is wrapped with an aluminum foil, and then covered with light-tight black tape. Both ends of the radiator are optically coupled to a SiPM which are used to detect the arriving photons. For the presented prototype detector we used a SiPM from Hamamatsu’s series MPPC S10362-33-100C. This device was primarily selected because of its large area of $3 \times 3$ mm$^2$.

This specific SiPM consists of 900 APDs of $100 \times 100 \mu$m$^2$ with a fill factor of 78.5%. Its nominal gain is $2.4 \cdot 10^6$ and it has a terminal capacitance of 320 pF. The maximum photo-detection efficiency is ~ 65% at 440 nm. Measurements of dark current, dark count rate and timing performance of this device have been presented elsewhere [12].

For testing the Cherenkov detector it is mounted in a light and vacuum tight aluminum box. The SiPMs are thermally coupled to water-cooled peltier elements, which allows to regulate
3. Test at the DAΦNE Beam-Test Facility (BTF)

The prototype Cherenkov detector was tested at the electron Beam Test Facility (BTF) at LNF, Frascati, Italy with e$^+/−$ of $\sim$ 490 MeV [14]. The aim was to make a proof of principle and to obtain a first measure of the timing resolution of this device with a Time-of-Flight (TOF) measurement in a real accelerator environment.

The BTF is one of the beam lines of the DAΦNE φ-factory. It is optimized for the production of electron/positron pulses with a wide range of multiplicities, including single particles. The maximum repetition rate is 50 Hz with a maximum particle flux of 1 kHz, so that at 50 Hz the maximum multiplicity is 20 particles. The beam profile has typical vertical and horizontal spot size of $d_v = 2 \text{ mm}$ and $d_h = 5 - 10 \text{ mm}$.

The beam diagnostics elements at BTF include a Pb-glass calorimeter. It is placed as last detector downstream after the Cherenkov counter in the beam line. The cross section of the calorimeter is $5 \times 5 \text{ cm}^2$ which is considerably larger than the ones of the other counters used for the test ($\sim 2 \times 10 \text{ mm}^2$). The beam particles are totally absorbed in the calorimeter so that the integrated signal from this detector provides a measure of the beam particle multiplicity. A typical energy spectrum of the calorimeter is shown in figure 2. The separate peaks correspond to beam pulses of 1, 2, 3 and more beam particles. This information allows to select beam pulses of a specific multiplicity by software in later data analysis.

3.1. Experimental setup

Figure 3 shows a schematic drawing of the experimental setup. There are four detectors relevant for the performed measurements. T1 and T2 are the reference counters for the TOF measurement, which consist of scintillators of 20 and 10 mm thickness, respectively and are read out on both ends by PMTs (Hamamatsu H8409-70). The Cherenkov counter C is placed between T2 and the calorimeter Calo. All detectors were centered on the central beam line. Data taking was triggered by a coincidence between T1, T2 and a spill gate. The BTF magnets were set to select e$^+/−$ with energies of $\sim$ 490 MeV.

The readout electronics was set up to measure charge spectra and TOF between the reference counters and the Cherenkov detector. A block scheme of the electronics setup is shown in figure 4. The signal output from each counter was split into
two lines. One was connected to a charge-to-digital converter (QDC, LeCroy ADC-2249W, 0.25pC/channel) for the charge measurement. The other line was fed into a leading edge discriminator and the outputs of the discriminator were relayed into a time-to-digital converter (TDC, Phillips 7186 with 25 ps per channel resolution) for time measurements and were also used to produce a gate signal for the QDC and a common-start signal for the TDC. All the QDC and TDC signals were recorded by a personal computer via Wiener CAMAC-CC32 PCI bus interface and stored in a hard disk for offline analysis.

Figure 4: Sketch of the read out electronics. The delay circuit for time adjustment is not shown here.

3.2. Measurements

During the measurements the temperature of the SiPMs was controlled to be $-16^\circ \pm 1$ C. The bias voltages of the SiPMs were both set to be 67.2 V as an optimization of gain and dark-count, which resulted in a signal pulse height of $\sim 8$ mV per fired pixel.

Figure 5 shows measured charge spectra of both SiPM devices of the prototype Cherenkov counter. The empty and striped histograms represent the distributions measured at beam-on (empty) and beam-off (striped) conditions. The background histogram is scaled so that the intensities in the first peak of both distributions are equal. Peaks corresponding to 1, 2, 3 and 4 fired-pixels are visible and well resolved. From the positions of the first four peaks in each histogram, the photon equivalent number of QDC channels ($QDC_{equiv}$) and the QDC offsets ($QDC_{off}$) is deduced. The number of photoelectrons ($n_{pe}$) corresponding to a given QDC channel is given by $n_{pe} = (QDC - QDC_{off})/QDC_{equiv}$.

The background distribution is dominated by the one-photon peak and decreases, in comparison with the beam-on distribution, rapidly towards higher photon numbers.

The filled histogram represents the signal distribution and is obtained from the empty histogram after selection of beam pulses with only one particle and events with good time information in both SiPMs. The number of random coincidences of larger than two photo-electron equivalent signals is negligible.

The time $T(i)$ of a detector $i$ (with $i = T1$, $T2$, $C$) is defined as the average TDC value of the corresponding left and right photo-sensors. The TOF between two detectors $i$ and $j$ is given by $TOF(i,j) = T(i) - T(j)$. Using the TOF measurements of all three possible pairs of detectors allows to disentangle the time resolution of each single detector and therefore to deduce the timing resolution of the Cherenkov counter.

For the data analysis, we selected single particle ($e^+/-$) events using the Calo energy spectrum. In addition a cut was applied to select those events in which both SiPMs of the Cherenkov counter had a proper timing information registered in the TDC. Note, that the Cherenkov detector did not join the trigger decision and therefore this cut reduced the number of available events drastically. Correction for slewing was applied to all counters. For the selected events the average number of photo-electrons detected in both SiPMs was estimated to be $\sim 8$ with rather broad distribution (filled histogram in figure 5).

Figure 6 shows the measured TOF distributions between pairs of detectors $T1$ and $C$ (left panel), $T2$ and $C$ (middle panel), and $T1$ and $T2$ (right panel). The solid lines are fits to the histograms using two independent gauss functions. With the resulting $\sim 360$ ps for TOF($T1$, $C$) and TOF($T2$, $C$) and $\sim 130$ ps for TOF($T1$, $T2$) a time resolution for the Cherenkov counter of $\sigma_{T(C)} \sim 350$ ps is obtained. The two reference counters, $T1$ and $T2$ have time resolutions of below 100 ps, which is well below the resolution of $C$. The accuracy of this measurement was limited by statistics and we estimate the error of $\sigma_{T(C)}$ to be in the order of 100 ps.

4. Discussion and Conclusions

We have reported on the beam test of a prototype Cherenkov detector with SiPM readout. Such a type of detector could be used as a beamline timing counter. In an experiment with an $e^+/-$ beam of $\sim 490$ MeV we detected the Cherenkov light induced by the particles passing through a slab of quartz with SiPMs and also measured TOF resolution in combination with reference counters.
The measured time resolution of the detector was found to be rather poor as a TOF counter (350 ± 100 ps). However, it is roughly in agreement with our previous measurements under laboratory conditions using a short pulse width laser (Advanced laser diode systems, EIG1000D+PIL040, pulse width 32 ps at wave length of 408 nm) with the same type of SiPM, pre-amplifiers and readout electronics at the given number of photons (400 ps at ~ 8 photons for one SiPM, 400/√(2) ~ 280 ps for the average of two SiPM) [12].

The average number of 8 photons detected in each SiPM is according to our offline measurement in the range of rapidly dropping time resolution as a function of the number of photons (see e.g. [13]) and therefore time resolution is expected to be improved by collecting more photons. Increasing further the thickness of the radiator from currently 1 cm is not a solution for all applications and would only help if the generated photons are effectively guided onto the SiPMs. It must be noted, that the shape of the radiator has not been optimized for efficient light collection. A simple calculation reveals, that a 490 MeV electron traveling through 1 cm of quartz generates around 300 photons in the wavelength range between 350 and 800 nm. Assuming an average photon detection efficiency of the SiPM of 30% in this wavelength range and neglecting all further losses, a maximum of 50 photons on each side of the radiator could be detected. With such a high number of detected photons the time resolution of the Cherenkov detector would be very much improved.

The other series of SiPM from Hamamatsu, S10362-11 has potentially better intrinsic timing performance (according to the product catalogue from [13]), however, due to the smaller sensitive area (1 mm²), the reduction of photon collection is expected to have a negative impact on the overall timing performance.

The measured rise time of the amplified signal under the condition of the beam test is 3 ns. This is significantly slower than the prompt photon generation from Cherenkov effect and also slower than scintillation light of, for example, commonly used Bicron BC-408 (time constant 2.1 ns). As the overall timing performance is a convolution of time response of photon generation, photon propagation, detector response and readout circuit the overall time resolution is limited by the slowest component.

The above mentioned 3 ns rise time is a convolution of intrinsic timing response of the SiPM device and the preamplifiers. We measured that the rise time of the applied preamplifiers, AMP_0611 from Photonique SA [13] is 2-3 ns depending on the input pulse height and therefore contributes significantly to the overall rise time of the SiPM signal. Thus using a faster preamplifier might also help to improve the overall time performance.

By improving the design of the radiator and using dedicated electronics for amplification and readout of the SiPM signals we are optimistic to be able to improve these results in future.

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