A Tracking Fiber Detector based on Silicon Photomultipliers for the KAOS Spectrometer

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Abstract—A tracking detector based on two meters long scintillating fibers read out by silicon photomultipliers (SiPM) is being developed for the KAOS spectrometer at the Mainz Microtron MAMI. Results from a prototype setup using 2 mm square fibers and large area SiPM readout are presented. The detection efficiency of such a combination was measured to be between 83 and 100% depending on the threshold on the SiPM amplitude. A Monte Carlo simulation based on a physical model was employed in order to extract the photon detection efficiency of the SiPM devices.

Index Terms—Silicon Photomultipliers, Particle Detection Efficiency, Tracking Detectors.

I. INTRODUCTION

The recently upgraded electron accelerator MAMI-C with beam energies up to 1.5 GeV has opened the door to kaon production experiments at the Institut für Kernphysik in Mainz, Germany [1]. The short orbit spectrometer KAOS has been added to the existing facilities allowing the detection of short living kaons with a high survival probability. The simultaneous detection of scattered electrons and positive kaons with this instrument at very forward angles will permit spectroscopic studies of hypernuclei by missing mass reconstruction. The spectrometer was successfully operated at GSI near Darmstadt in heavy ion collision experiments. In order to cope with the planned experiments at MAMI the existing detector system has to be completed with a package for the electron momentum and track reconstruction. Timing and position information can be obtained simultaneously by scintillating fiber tracking detectors. Multianode photomultipliers (MaPMT) have been used as readout devices for the vertical component of a detector of this type. Experience has shown that there are several drawbacks associated with MaPMT. In particular, optical cross-talk among neighboring channels has been observed giving rise to a reduced position resolution [2]. In addition the need for high voltage supplies and magnetic shielding increases the overall price and complexity of the detector [3].

Moreover, a light sensor for the horizontal component of the tracking detector has to be capable of a reliable operation in vacuum. Silicon photomultipliers (SiPM) are emerging as a solid state alternative to conventional photomultipliers in many fields. Hundreds of micrometric avalanche photodiodes (APD) connected in parallel are operated in a SiPM beyond the breakdown voltage for a high gain of $10^6$ [4].

II. SCINTILLATING FIBERS WITH SiPM READOUT AS TRACKING DETECTORS

SiPM have been suggested as possible readout device for the 150 two meters long scintillating fibers forming the horizontal detector. Magnetic field insensitivity, small volume, sensor independence, good vacuum performance and low voltage operation make SiPM interesting for this application. Low light level detection is on the other hand challenging for these devices due to their high dark count rate. Long and thin fibers will only be capable of guiding a few photons to the detector surface due to the low energy deposition of minimum ionizing electrons and the strong light absorption. Detection efficiency is a major issue for a tracking system and the right combination of fiber and SiPM has to be carefully studied. Radiation hardness studies have also been performed showing that commercially available SiPM suffer from a large increase in leakage current for relatively low radiation doses [5]. This poses an additional problem for their use in combination with long scintillator fibers. The leakage current will appear as a high rate of single photoelectron signals due to the avalanche amplification specific of photodiodes operated in the limited
Geiger mode.

Fig. 2 shows a typical ADC spectrum recorded for a 1 mm² device from Photonique type number SSPM-0701BG-TO18. The bold-dashed curve is the result of a Monte Carlo simulation including the main operating parameters of SiPM as optical cross-talk, after-pulsing, photon detection efficiency (PDE) and gain variations developed in order to extract the mean number of detected photons. This method is necessary due to the overestimation that is quoted in many publications where the effect of optical cross-talk and after-pulsing is not subtracted. SiPM are manufactured so that signal uniformity from pixel to pixel is quite good, typically within 10%. The small gain variation together with the narrow single electron response function of each APD provides excellent photon counting capabilities as can be appreciated in the well defined peak structure of the spectrum.

It is well known that SiPM noise rate is mostly due to single pixel signal. Rates of the order of several megahertz at room temperature are normal in today’s commercially available SiPM. An avalanche of $10^6$ carriers in any of the micrometric APD forming the SiPM will create around 50 photons via hot carrier luminescence with enough energy to trigger any neighboring pixel. This phenomenon is known as optical cross-talk and explains the measurable dark rate for threshold beyond one pixel signal amplitude. These signals compete with real signals generated by a small number of photons. A simple model based on the probability $q$ of single neighbor activation allows the probabilities for the different clusters of APD to be calculated (only pixels sharing one complete side are allowed as members of a cluster). Cluster probabilities are given by the zero pixel cross-talk probability $P(0) = (1-q)^4$, and the $N$-pixel cross-talk probabilities $P(1) = 4q(1-q)^6$, $P(2) = q^2[6(1-q)^8 + 12(1-q)^7]$, and $P(3) = q^3[32(1-q)^8 + 32(1-q)^9 + 8(1-q)^{10}]$.

III. MEASUREMENTS ON SIPM PERFORMANCE

Previous studies performed with 0.85 mm diameter 2 m long cylindrical fibers read out by Photonique SiPM with an active area of 1 mm² showed that the small number of generated photons was a serious concern for efficient electron detection. Fig. 3 shows the mean ADC value as function of the applied voltage for this SiPM. The almost linear dependency allows to conclude that low voltages are more appropriate for low light level detection due the much faster increase (exponential) in the dark count rate with voltage. The differences in the measurements for the two devices are not fully understood although manufacturing variability seems to be the most probable explanation. The measured linear dependence is explained by the linear increase in avalanche probability and diode capacity charging.

Fig. 2. ADC spectrum for a Photonique device of 1 mm² cross-section with type number SSPM-0701BG-TO18 illuminated by a low intensity light source. The position of the pedestal peak is indicated by a vertical line, the following peaks resolve the signals from single and multiple pixels of the SiPM. The peak structure is due to the narrow response function. The bold-dashed curve is the result of a Monte Carlo simulation including the main operating parameters of SiPM.

Fig. 3. Mean number of detected photons and single pixel amplitude as a function of the bias voltage for two Photonique devices of 1 mm² cross-section with type number SSPM-0701BG-TO18. The observed differences between the two curves are not fully understood but manufacturing variability seems to be the most probable explanation. The measured linear dependence is explained by the linear increase in avalanche probability and diode capacity charging.

Fig. 4. Dark count rate as a function of threshold level measured for two large area SiPM SSPM-0606BG4MM-PCB and for a 1 mm² device. The dark count rate is a factor of four higher for the larger devices and steps are less defined due to the more probable signal pile-up.

1Photonique SA, http://www.photonique.ch (2008)
minimum particle trajectory disturbance is important for a tracking detector. Fibers of 4 mm$^2$ cross-section will only increase the amount of generated light by a factor of 2 but noise in the SiPM will be 4 times larger due to the fact that dark count rate increases linearly with the detector surface. The improvement comes from the fact that high efficiencies can be achieved with higher thresholds for the larger cross-section fibers and the geometrical reduction of dark count rate with threshold level will allow an effectively lower rate.

Fig. 5 shows the setup for characterizing a two meters long Bicron BCF-20 fiber read out in both extremes by the large area SiPM. Signals are brought into a compact electronic board incorporating a SiPM bias circuit and a transimpedance amplifier optimized for the amplification of SSPM signals. The coupling to the scintillating fiber is direct. No optical connection is necessary due to the small difference in the refraction indexes of the protecting epoxy layer used for the SiPM and the fiber core material. A Plexiglas connector was designed that allowed a reliable connection and mechanical stability of the full assembly as well as optical control of the relative position of fiber to SiPM for a proper alignment. A 250 cm long light tight box was constructed to keep the experimental arrangement protected from external light sources. The voltage for the preamplifiers and the SiPM was constantly monitored and the temperature was measured to be stable within 2°C. Light absorption was measured by exciting the fiber at several points with a beta source and by determining the corresponding change in the mean ADC value, see Fig. 6. The measured absorption length of 1.5 m is substantially smaller than the value quoted by the manufacturer (> 3.5 m for 1 mm diameter fiber measured with a bialkali cathode PMT) which needs clarification.

A simple calculation shows the equivalence of the energy loss in scintillating fiber tests made with the $^{90}\text{Sr}$ source to the loss of high energy electrons. $^{90}\text{Sr}$ is an beta-source with a maximum kinetic energy of $E_{\text{max}} = 546\text{ keV}$ and a mean kinetic energy of $E = 196\text{ keV}$. It decays to $^{90}\text{Y}$ with a half-life of 29.12 y. The short-lived daughter decays with a maximum kinetic energy of $E_{\text{max}} = 2.28\text{ MeV}$ and a mean

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2Bicron, [http://www.bicron.com](http://www.bicron.com) (2008)
TABLE I

| Threshold (pixel) | 2 mm Fiber / 4.4 mm² SiPM | 0.86 mm Fiber / 1 mm² SiPM |
|------------------|--------------------------|--------------------------|
| Efficiency (%)   | Random Rate (kHz)        | Efficiency (%)           | Random Rate (kHz) |
| 0.5              | 100                      | 2000                     | 91              | 320          |
| 1.5              | 99.8                     | 80                       | 76              | 5            |
| 2.5              | 95.0                     | 1.3                      | 56              | 0.45         |
| 3.5              | 82.6                     | 0.04                     | 35              | 0.04         |

IV. CONCLUSION

The KAOS spectrometer at MAMI will be extended by a large fiber detector in the near future. Our study has shown that the readout of 2 mm square scintillating fibers by SiPM can lead to near 100% detection efficiency for electrons. A random coincidence rate for a setup of two 4.4 mm² large area SiPM is unavoidable because of high dark count rate of these devices. However, with a reasonable threshold setting and further trigger conditions such a system is feasible.