Future use of silicon photomultiplier for KAOS at MAMI and PANDA at FAIR

P. Achenbach\textsuperscript{a,}*, S. Sánchez Majos\textsuperscript{a}, J. Pochodzalla\textsuperscript{a}

\textsuperscript{a}Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany

Abstract

A characterisation of recently developed SiPM was performed in view of their possible application with scintillating fibres. The use of SiPM as part of the fibre tracking detector system of the KAOS spectrometer at MAMI was studied. A concept of similar SiPM/fibre assemblies is being considered for the time-of-flight start detector in the PANDA experiment for the FAIR project. In summary, the devices are very suitable for low light yield detection insofar a mechanism is found to cope with the noise rate characteristics and radiation hardness.

Key words: Tracking and position sensitive detectors, Silicon photomultiplier, Scintillating fibres, Monte Carlo model for detector output, radiation damage

1. Introduction

The time-of-flight (TOF) method has been used for a long time for particle identification in the low momentum range. A detector based on small cross-section scintillating fibres can combine the TOF information with coordinate information. Three main requirements must be fulfilled of such a system: 1) high particle detection efficiency at minimum thickness, 2) sufficient radiation hardness, and 3) fast time response.

The SiPM is a novel semiconductor photodetector operated in the limited Geiger mode, capable of resolving individual photons \cite{1, 2}. In combination with scintillating fibres a SiPM can provide a relatively cheap and reliable tracking detector operated with low voltage, magnetic field insensitive and minimal volume. The SiPM is intrinsically a very fast detector and its single photoelectron time resolution is about 100 ps (FWHM). When coupled to thin and short scintillating fibres the timing properties are fully dominated by the scintillation time constants and depend only on the average number of detected photons.

A critical issue in the operation of SiPM/fibre assemblies, especially when such a detector is self-triggering, is the noise rate. Two paths are followed in our development of SiPM/fibre tracking systems: Firstly through the increase of the signal amplitudes by carefully matching the geometries and spectral responses, and secondly through the use of a versatile trigger selecting the wanted processes and suppressing the majority of background events.

For this paper the characteristics of SiPM from different manufacturers coupled to round and square scintillating fibres of several diameters were studied.

Table 1: Measured detection efficiencies as a function of discriminator threshold in units of single pixel amplitude. The set-up consisted of a 2 m long fibre of 0.83 mm diameter and three reference counters.

| Threshold (no. of pixels) | Efficiency (%) |
|--------------------------|----------------|
| 1                        | 91             |
| 2                        | 76             |
| 3                        | 56             |
| 4                        | 35             |

2. SiPM in KAOS tracking detectors

At the Institut für Kernphysik in Mainz, Germany, the microtron MAMI has been upgraded to 1.5 GeV electron beam energy and can now be used to study strange hadronic systems. A large fibre detector set-up is under development for the KAOS spectrometer \cite{3}: the coordinate detector of the spectrometer’s electron arm will consist of two planes of vertical fibre arrays, covering an active area of $L \times H \sim 2000 \times 300 \text{ mm}^2$, supplemented by one or more planes with horizontal fibres. The read-out of the vertical fibres will be performed one-sided by multi-anode photomultipliers. The experience acquired in the design and beam-test of these detectors has suggested that the use of multi-anode photomultipliers with several fibres per pixel introduces a relatively high degree of complexity. SiPM have been suggested as a possible candidate for a two-sided read-out for the long fibres in horizontal direction. Their use would simplify detector mechanics and reduce considerably the over-all cost. Low light yields have been measured with 0.83 mm diameter, cylindrical fibres. Up to now the high intrinsic noise count rate of SiPM has limited their use to cases in which tens or hundreds of photons are available. Gain variations from diode to diode and temperature dependence are further problems to be considered.

\*Corresponding author. Tel.: +49-6131-3925831; fax: +49-6131-3922964.

Email addresses: patrick@kph.uni-mainz.de (P. Achenbach)

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The detection efficiency is a major issue in designing a tracking system and the right combination of fibre and SiPM has to be found. Table 1 shows the results of the efficiency measurement for a 2 m long double cladding 0.83 mm diameter fibre, read out in both extremes by the 1 mm$^2$ Photonique device SSPM-0701BG-TO18 [4]. Minimum ionizing particles are chosen by their energy deposition in a thick scintillator and coincidences with two diametrically opposed fibres read-out by conventional photomultipliers are required for a countable event. High efficiencies were only obtained with very low discriminator thresholds. Larger diameter, square fibres are generating enough light to get an acceptable detection efficiency for higher thresholds reducing considerably the noise level. We concluded that a 4 mm$^2$ double cladding fibre with 4 mm$^2$ SiPM read-out can be used for the KAOS spectrometer’s electron arm tracking detector.

Depending on the bias voltage the SiPM show a noise count rate of up to 1 MHz even for thresholds above 1 pixel, see Fig. 1. In order to define the hit position in the fibre detector, a fast clustering algorithm is needed. Coincidences between left/right signals are mandatory. Further, the spectrometer will be used for experiments with very different experimental conditions. As a consequence, a versatile trigger system is mandatory which can be easily reconfigured and adopted to the experimental requirements. It is obvious that a simple TOF trigger does not fulfill these requirements. For KAOS the trigger is based on fast, programmable multi-purpose logic modules which have been developed recently at the GSI. Each so called VUPROM module (VME Universal Processing Module) has 256 channels I/O with an high speed differential LVDS standard.

### 3. SiPM in PANDA time-of-flight detectors

At PANDA relatively low momentum Ξ$^-$ can be produced in Ξ$^-$Ξ$^+$ or Ξ$^-$Ξ$^0$ pair productions [5]. The associated Ξ will scatter or annihilate inside the residual nucleus. The annihilation products contain at least two anti-kaons that can be used as a tag for the reaction. In combination with an active secondary target, high resolution γ-ray spectroscopy of double hypernuclei will become possible for the first time. For the tracking and stopping of the produced cascade hyperons and their decay products an active hypernuclear target is needed. For the high resolution spectroscopy of excited hypernuclear states an efficient, position sensitive germanium array is required. A small fibre barrel read-out by SiPM has been discussed as an option for a time-of-flight start detector in PANDA and as the active target for the hypernuclear Physics programme. Such a detector might be also used as a time reference for the DIRC detector or for track deconvolution of the time projection chamber. For PANDA the time resolution is a main issue.

The time resolution of a single SiPM/fibre assembly when excited by minimum ionizing particles crossing its center was measured by taking the time difference between the left and right signal simultaneously to the pulse-height spectrum. A gate on individual peaks made it possible to determine the time resolution as a function of the no. of fired pixels as is shown in Fig. 2. With the set-up discussed in Section 2 single SiPM resolutions of 1.69 ns (rms) for 1 pixel, and 1.40, 1.26, 1.23, 1.21 ns (rms) for 2–5 pixels were determined. The time distributions are non-Gaussian and are well described with exponential functions. To determine the photoelectron yield from the pulse-height spectrum as shown in Fig. 3 a multi-Poissonian fit of the fol-
lowing type was performed:

\[
f(q) = \sum_{p=0}^{15} \sum_{s=0}^{15} \left( \frac{\exp^{-\lambda q}}{p!} \right) \left( \frac{\exp^{-\mu s}(p\mu)^s}{s!} \right) \times \frac{\exp \left( -\frac{1}{2} \frac{(p+s)^2}{\sigma_0^2 + (p+s)\sigma_1^2} \right)}{\sqrt{2\pi}\sqrt{\sigma_0^2 + (p+s)\sigma_1^2}}\]

with \( q = \frac{x - x_0}{g} - n l \cdot \frac{x - x_0}{g} \), \( x, x_0 = \text{ADC counts, pedestal off-set, } p, \lambda = \text{photon counts and mean value, } s, \mu = \text{secondary pixel counts and mean value, and } \sigma_0, \sigma_1 = \text{pedestal and pixel noise.} \) By using this fitting method, which takes optical cross-talk into account, mean numbers of photons and pixel noise. By using this fitting method, which takes optical cross-talk into account, mean numbers of photo-electrons \( \overline{N} \sim 4 \) were measured with a \(^{90}\text{Sr}\) source. A Monte Carlo model for photon generation and tracking was applied to 10 cm long double cladding fibres to verify the measurements for a possible \( \text{PANDA} \) detector. Based on the simulation a time resolution of 0.9 ns (rms) is expected.

A full GEANT4 simulation of the \( \gamma \)-ray spectroscopy set-up with several germanium cluster detectors has been completed [4]. The simulation was performed using a demanding time-of-flight (TOF) detector system for low momentum kaon identification: a start detector of \( \sim 2000 \) scintillating fibres placed in two rings and a TOF barrel detector of 16 slabs. As can be deduced from the results seen in Fig. 4 a time resolution of \( \sigma < 100 \) ps needs to be achieved in the stop detector, whereas the fibre detector has to provide the start time with a minimum resolution of \( \sigma \sim 400 \) ps. It seems clear that these values cannot be reached with the geometries and detectors studied so far. Our approach is to match SiPM with enhanced green sensitivity to fibres with green scintillation light. A first test with a large diameter SiPM/fibre combination has shown a signal amplitude increase by a factor of 2.

\[\text{References}\]
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