Detector Design Studies For High Precision Particle Physics Experiment

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Timothy Blake Watson
High Energy Physics Group
Department of Physics
The University of Texas at Arlington

Abstract

High-energy physics is the field of physics utilizing powerful high-energy particle accelerators to probe and understand the fundamental particles of nature and the forces between them. Among the great accomplishments of the field of particle physics is a theoretical model that explains many of the phenomena we see in our universe: the Standard Model. While the Standard Model has been very successful in describing nature, it is necessary to push the limits of this model in an effort to truly understand its predictability. This search for new physics beyond the Standard Model requires the construction of next generation particle detectors capable of extreme high-precision measurements. The ORKA experiment, currently in the proposal stage, will search for rare kaon decays that may contradict Standard Model predictions and presents a paradigm changing new physics. In this talk, I will outline in detail design studies for the range stack, an essential detector component UTA is responsible for, incorporating novel components, specifically silicon photomultipliers (SiPMs) in place of photomultiplier tubes (PMTs) and the Gas Electron Multiplier (GEM) technology.

1. Introduction

The purpose of the ORKA experiment, located at the Fermi National Accelerator Laboratory, will be to investigate and measure specific rare kaon decays that are uniquely susceptible to new physics beyond the standard model. These decays have branching ratios as small as 10^{-11}, and therefore the detector of ORKA must be both sensitive enough to detect these decays and accurate enough to eliminate background decays. To ensure this, every major component of the detector must be individually studied to ensure its efficiency. UTA has been tasked with the assembly of the range stack, the section of the detector that is responsible for tracking the position of charged particles emanating from the decaying kaons. The range stack is primarily composed of scintillators, light gathering electronics, and high precision particle trackers. There are many exciting new technologies that have developed in the past decade that would make ideal candidates for inclusion over other, older alternatives. Among these are silicon photomultipliers and the gas electron multiplier. The following presents the research done in studying the benefits of these devices and the reasons behind their selection for inclusion in the range stack.

2. Analysis

The bulk of the research conducted was in the analysis of the components being considered: the silicon photomultiplier and the gas electron multiplier. Numbers provided for the silicon photomultiplier may be slightly dated — as with any new technology, the rapid development and commercial availability of improved devices is unmatched by the pace of the literature regarding the performance of the devices. With that said, I have made an effort to reflect the most accurate numbers presently available.

2.1 The Silicon Photomultiplier

The silicon photomultiplier (SiPM) is a semiconductor device consisting of an array of avalanche photodiodes (APD) operated in Geiger mode capable of single photon detection. The SiPM ranges in size, but current devices typically measure from 1 to 10 millimeters square, with as many as 1600 APD pixels as small as 50 to 70 μm constituting the photosensitive area as seen in Fig. 1. For each of these pixels there is a recovery time associated with every detection event when the triggered APD is temporarily "blinded" by feedback current and unable to detect additional photons. A resistor quenches this current, but the recovery time can last as long as a few microseconds before the pixel can resume operation, depending upon the model and manufacturer of the SiPM. The spectral response of any given SiPM varies, but on average the devices are sensitive to wavelengths between 320 to 900 nm

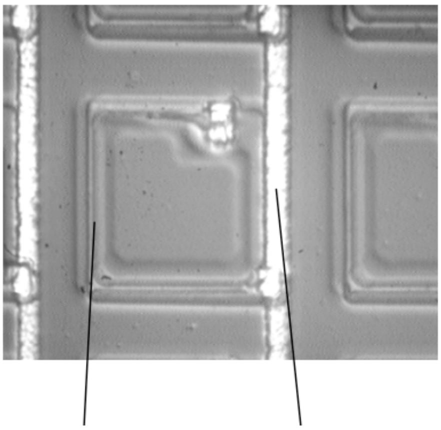

Figure 1:
A magnified view of a single APD pixel on the surface of a SiPM. The white band to the right is an Aluminum conductor. [2]

with peaks between 400 to 700 nm. The following table gives additional information about SiPMs as well as a comparison between the silicon photomultiplier and other photon detectors, specifically photomultiplier tubes (PMT). Of particular note are the equivalent gains and threshold sensitivities as well as the SiPM's lower operating voltage and the PMT's problematic operation in a magnetic field.

Table 1:

	PMT	APD	HPD	SiPM
Photon detection efficiency:				
blue	20%	50%	20%	12%
green - yellow	a few %	60-70%	a few %	15%
red	<1%	80%	<1%	15%
Gain	10^6-10^7	100-200	10^3	10^6
High voltage	1-2 kV	100-500 V	20 kV	25 V
Operation in the magnetic field	problematic	OK	OK	OK
Threshold sensitivity $S/N \gg 1$	1 ph.e.	~10 ph.e.	1 ph.e.	1 ph.e.
Timing /10 ph.e.	~100 ps	a few ns	~100 ps	30 ps
Dynamic range	$\sim 10^6$	large	large	$\sim 10^3/mm^2$
Complexity	high (vacuum, HV)	medium (low noise electronics)	very high (hybrid technology, very HV)	relatively low

Table 1: A comparison of photomultiplier tubes (PMT), avalanche photo diodes (APD), hybrid photodetectors (HPD), and silicon photomultipliers (PMT).

2.2 The Gas Electron Multiplier

The gas electron multiplier detector (GEM) is a gaseous detector capable of higher gains than multiwire proportional chambers consisting of several layers of copper-coated kapton foil with acid-etched evenly spaced holes as seen in Fig. 2 is placed in a gas chamber of Ar/CO_2 positioned between an anode and a cathode. A voltage is applied to both sides of the kapton. Electrons created by the passing of a charged particle through the detector are accelerated through the kapton foil creating cascades of secondary ionized particles and thereby improving the gain of the detector. Current GEM detectors are capable of position resolutions as small as 40 -50 µm.

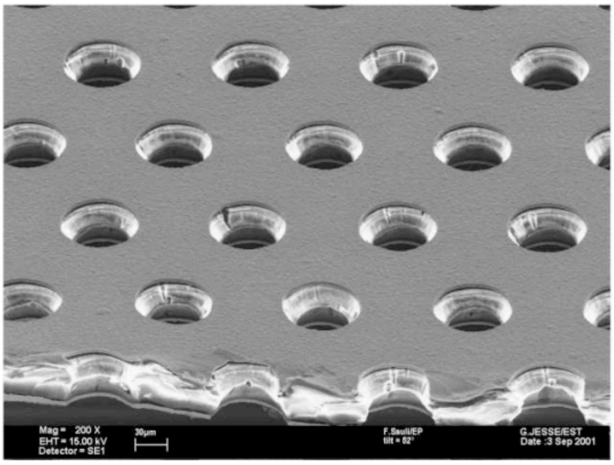

Figure 2: A scanning electron microscope image of the copper-coated Kapton foil. [3]

2.3 Range Stack GEM Design

In incorporating the GEM chambers effectively about the range stack, it is necessary to design a triple GEM as seen in Fig. 3a to cover multiple azimuthal sections. This serves to mitigate costs associated with the number of voltage supplies, gas regulation equipments, and data acquisition electronics each GEM detector requires. The triple GEM, constructed from three layers of GEM foil, is chosen because of its high gains and reliable performance. The readout strips are arranged as seen in Fig. 3b with *u* and *v* strips arranged at offset angles (non-perpendicular) allowing for accurate position resolution of incident ionizing particles from either end of the GEM .

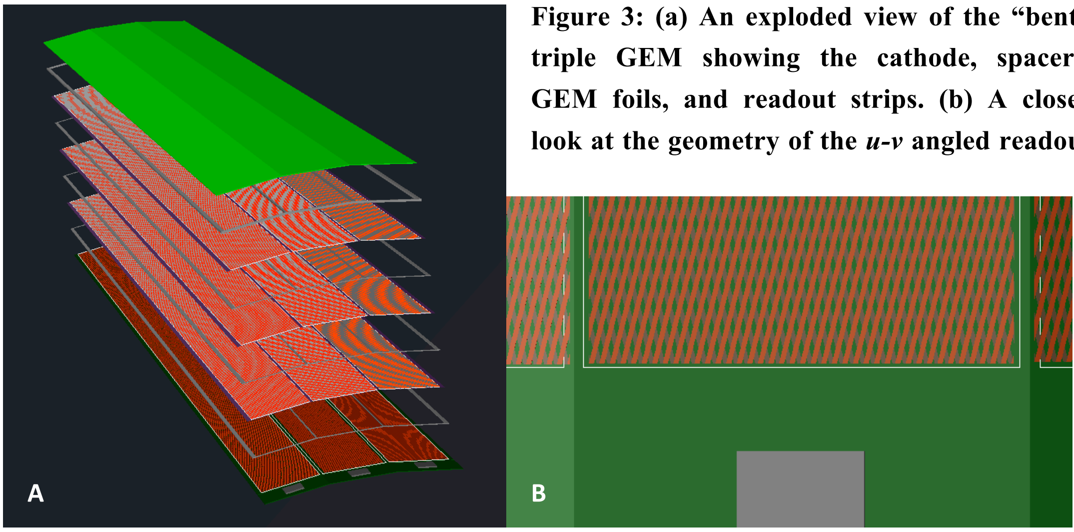

Figure 3: (a) An exploded view of the "bent" triple GEM showing the cathode, spacers, GEM foils, and readout strips. (b) A closer look at the geometry of the *u*-*v* angled readout

3 Result and interpretation

An important characteristic of semiconductors is their imperviousness to magnetic fields. This plays a large role in deciding between SiPMs and PMTs for inclusion in the range stack, as the ORKA detector will be entirely encased in a large, powerful magnet. Yet other aspects of the SiPM also factor in to its preference over PMTs including the compact size, relative simplicity, and lower operating voltage. The GEM offers extremely high resolutions, higher than those possible for the alternative straw-tube tracker. However, what exactly this means for the underlying physics remains unclear.

4 Conclusions and future work

I found that SiPMs and GEM detectors offer several distinct advantages over the alternative technologies proposed for inclusion in the ORKA experiment. However there still remains much work to be done in determining the finer points of incorporating the individual components into the ORKA design. Few studies are available for determining how to best attach SiPMs to scintillators in a way that maximizes performance and decreases the loss of light. In the interest of due diligence, it would be best to build small scale portions of the range stack and test the best way to go about assembling the full scale detector. Additionally, simulations will be the best way to determine if adding GEM detectors in place of straw tube trackers provides enough benefit to improved understanding of the underlying physics to warrant its more expensive price.

5 Bibliography:

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3. De Smet, V. “Study of a GEM tracker of charged particles for the Hall a high luminosity spectrometers at Jefferson Lab” Master’s Thesis. Università Degli Studi Di Catania. (2011)