ADVANCES IN MULTI-PIXEL PHOTON COUNTER TECHNOLOGY*

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Abstract

The multi-pixel photon counter (MPPC), or Geiger-mode avalanche photo-diode (GM-APD), also known as silicon photomultiplier (SiPM) is of great interest as a photon detector for high-energy physics scintillation counters, and other applications. In this paper we discuss some of the performance characteristics of MPPCs, and several applications, namely for muon cooling experiments, rare muon decay modes, and collider detectors. In addition we will discuss advances in signal processing electronics for MPPCs, which further enhance their use for large-scale applications.

INTRODUCTION

A few years ago the MPPC emerged as a new type of photon detector with promise of supplanting vacuum photo-multiplier tubes (PMTs) in many applications. MPPCs operate at low voltage (~50V) are immune to high magnetic fields, provide good photon detection efficiency, have high gain and good single photoelectron resolution, are small in size, and can potentially be produced at lower cost than conventional PMTs. MPPCs are solid state devices, typically about 1 square mm to several square mm in area, and subdivided into pixels (up to 1600 currently) by implementing a grid of narrow barriers between active areas.

MPPC CHARACTERISTICS

MPPCs operate as avalanche photo-diodes in the limited Geiger mode. That is, the bias voltage is set slightly above the breakdown potential (overvoltage) so that individual photons produce a standard signal in the pixel that is hit. Thus the overall signal response consists of the sum of the signals from all of the pixels that are hit by photons. The resulting pulse height spectrum consists of a series of peaks, each corresponding to a particular number of photoelectrons [1], as shown in Figure 1. The peaks are well separated because the pixels produce nearly identical signals and high gain. This makes them useful for low-light applications, where small signals of a few photoelectrons need to be distinguished from noise pulses. Until recently, MPPCs have not been available commercially, but now several manufacturers offer them on the market.

MPPC output is dependent on temperature and overvoltage [2] as shown in Figure 2. Other characteristics that are important for MPPC operation are noise rates and cross-talk. MPPCs are noisier than vacuum PMTs, and noise rates are also temperature and overvoltage dependent. Cross-talk of early pre-production versions has been reduced to a few percent in production versions.

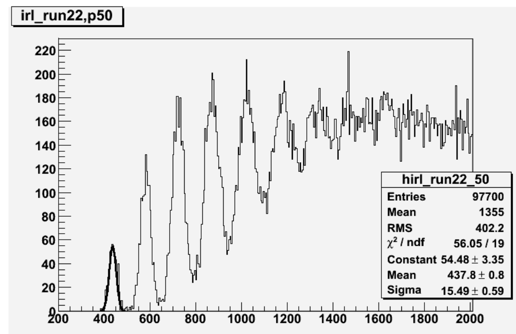

Figure 1: Output pulse height distribution from an MPPC interfaced to a plastic scintillator with a radioactive source. Note the clearly defined peaks corresponding to discrete numbers of photoelectrons.

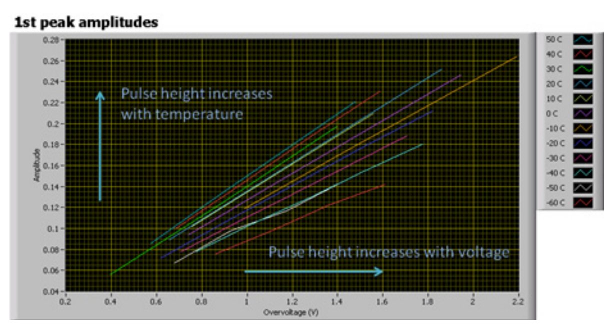

Figure 2: MPPC signal amplitude vs. overvoltage for temperatures between -60C and +60c. Overvoltage is the increase in bias voltage above the breakdown potential.

NEW MPPC APPLICATIONS

Scintillating Fiber Tracking for MANX

The MANX experiment has been proposed to run at the Rutherford-Appleton Laboratory in the UK [3]. Its purpose is to measure the emittance reduction of a muon beam as it passes through a helical cooling channel (HCC), which is depicted in Figure 3. Detector planes of scintillating fibers are mounted inside the cooling channel to measure the trajectories in the channel. MPPCs are being considered for use as photon detectors, as shown in Figures 3, 4, and 5. In this application the MPPCs will operate at liquid helium temperature.

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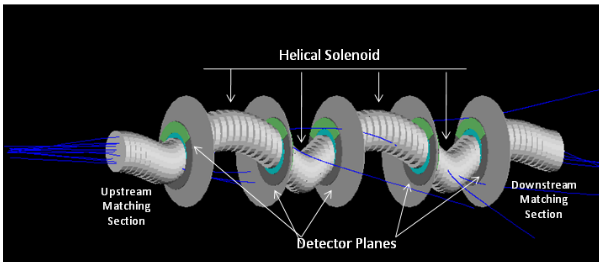

Figure 3: Schematic representation of the MANX cooling channel with 5 sets of trackers inside. The first tracker is mounted between the upstream matching magnet and the HCC, three trackers are built into the HCC coil structure, and the last tracker is between the HCC and the downstream matching magnet. The trackers alternate between x-y and u-v units.

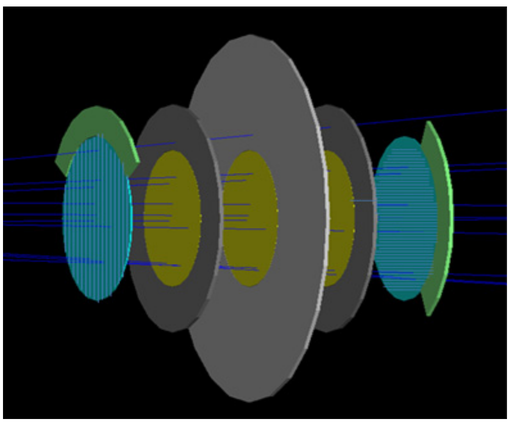

Figure 4: Exploded view of an x-y tracker unit. The central disk is a mounting plate that is permanently installed in the coil structure. Next are the detector support rings, and outer scintillators and electronics, which are built as units that are installed on the central mounting plate. The yellow disks represent liquid helium that fills the HCC volume.

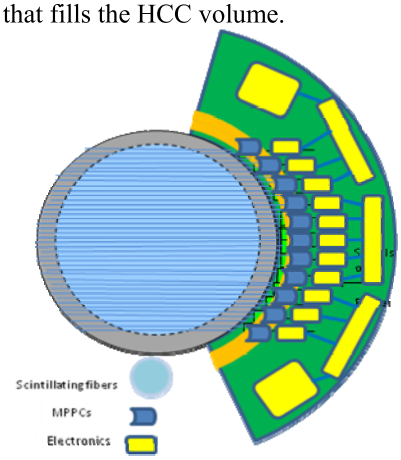

Figure 5: Layout of scintillators, MPPCs, and electronics for a typical detector plane in the MANX cooling channel.

Calorimeters for the Mu2e Experiment

An application that can be improved by use of MPPCs is the electromagnetic calorimeter in the recently approved neutrino-less muon-to-electron conversion experiment (Mu2e), E-973 at Fermilab [4]. In the proposal there is an electromagnetic calorimeter that is made up of 1800 lead tungstate crystals, arranged in 4 sets with avalanche photodiodes. The detector is shown in Figure 6. Electrons (shown in green) emitted from negative muons (shown in red) that stop and are captured in the stopping target strike the calorimeter after passing through the tracker and the calorimeter provides a trigger and a redundant measurement of the electron energy. The crystals and photodiode are operated at a temperature of -24C, to increase light yield of the PbWO4 crystals and to reduce noise from the avalanche photo-diodes (APDs). By changing to LYSO crystals, which have higher gain and need no cooling, and MPPCs, which can operate at room temperature, the performance of the calorimeter is improved and the need for refrigeration is eliminated.

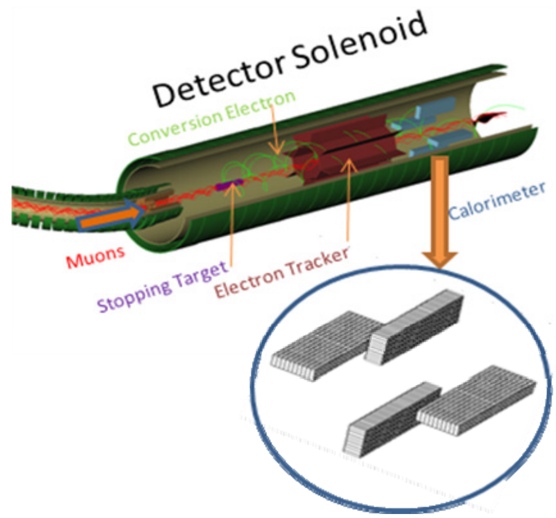

Figure 6: Mu2e detector. Electromagnetic calorimeter is shown in more detail. MPPCs could be used as photon detectors for the calorimeter.

ELECTRONICS FOR MPPCS

One of the advantages of MPPCs is their small size, but to fully exploit this, it is necessary to integrate small-footprint front-end electronics to the MPPCs. To this end, new electronics, optimized to support the characteristics and applications of the devices, such as ASICs, are needed. Effective utilization of the MPPC photon detectors will be greatly enhanced by integrating the signal detection and front end processing functions in an ASIC. Additional signal processing functions such as analog to digital conversion, time to digital conversion, as well as some logic functions that have previously been performed by racks of modules, could also be provided by the ASIC. The electronics industry is moving toward 3-dimensional integrated circuit (3D IC) technology, and it may be particularly good for supporting MPPCs.

FPGA-Based Integrated Readout Layer

The NIU group has worked with Fermilab to develop an integrated system of scintillator tiles with MPPCs and

FPGA-based readout [5]. The MPPCs are optically interfaced to the tiles without light guides. This system is being developed as prototypes for the CALICE hadron calorimeters for use at collider experiments. Figure 7 shows a module with an array of MPPCs mounted directly on a PC board that has its FPGA (field programmable gate array) readout electronics. This design eliminates fiber light guides that usually are used to carry the optical signals from the scintillator to the photon detector. The small size of the MPPC allows finer granularity than vacuum PMTs.

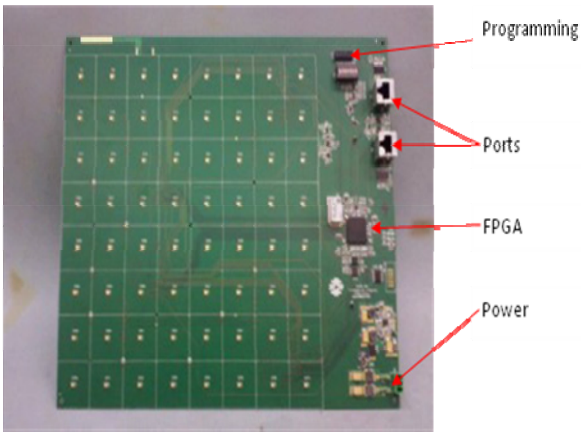

Figure 7: Array of 64 MPPCs mounted on the same board as the readout electronics.

3D IC Readout Electronics for MPPCs

The next generation of integrated electronics (3D ICs) is very promising for use with MPPC detectors as well as for silicon pixel detectors for collider experiments [6]. Comparison of the functions of conventional 2D electronics and 3D IC electronics is illustrated in Figure 8.

In the 2D version the photon detector (PD) shares the sensitive surface with the readout electronics (shown in blue) and the processing and addressing functions. In the 3D IC version the entire upper layer is covered with photon detectors. The readout integrated circuits are in the middle layer, and the processing functions are in the lower layer. For the CALICE calorimeter application the dead space for the FPGA electronics is eliminated. For the MANX application the readout electronics needed for each fiber can be integrated with each MPPC, and reduce the size of the electronics on the readout boards.

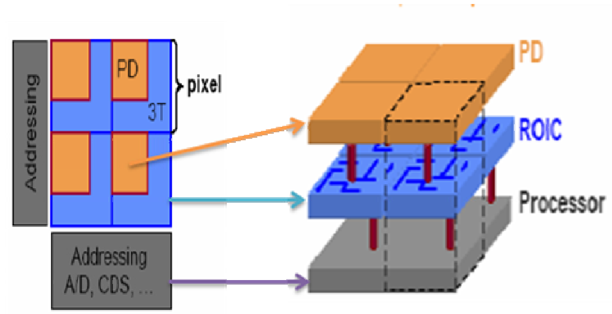

Figure 8: Correspondence of the functions of an optical detector using conventional 2D technology and one using 3D IC technology. The photon detector (PD), readout (RO) and processor functions are shown

SUMMARY

We have shown several examples of how MPPCs and integrated electronics can be used to improve particle detectors for high energy physics and accelerator experiments. In addition there are many other fields in which these advances can be applied, such as medical applications such as PET scanners, space-based detectors, and industrial areas where photon detection is important.

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