Review Committee Report on Silicon Photomultiplier R&D at Fermilab

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1. Review Agenda

A review of silicon photomultiplier R&D work at Fermilab was held on the afternoon of February 17, 2009. Presentation titles and speakers are given in the table below:

SiPM Characterization	Adam Para
SiPMs at MTest	Anatoly Ronzhin
CMS Plans	Jim Freeman
Muon Detector R&D	Gene Fisk
Plans for Readout	Paul Rubinov
Dual Calorimetry	Adam Para

Note: There are many variations on the term, "silicon photomultiplier": Geiger-mode Avalanche Photodiode, Multi-Pixel Photon Counter, Pixel Photon Counter, Photon Counting Detectors, etc. All refer to a silicon detector of optical photons based on an array of photodiodes each with a size of a few tens of microns on a side, and operated at a bias voltage of $\sim 30 - 70$V. For convenience, we use throughout the common abbreviation SiPM to refer to the devices.

2. Overview of SiPM Potential and Production

SiPMs are a relatively new type of photon detector that potentially offers an attractive replacement for conventional photomultiplier tubes (PMTs) in many applications. Their **advantages** compared to PMTs include

- Ability to produce gains of $10^5 - 10^7$ for bias voltages of a few tens of Volts,
- Insensitivity of response to magnetic fields,
- Small physical size allowing incorporation onto the body of a detector,
- Excellent discrimination of individual photons for low numbers of detected photons due to the standard pulse height produced by the individually "fired" pixels,
- Robustness as evidenced by the ability to be exposed while biased to high light levels (e.g. normal room lighting) without damage to the SiPM.
- Potential low cost per unit (currently \$50-200 each for $1\text{mm}^2 - \sim 10\text{mm}^2$ active area).

However, SiPMs also present their own particular set of **disadvantages**:

- Large dark noise at room temperature (10s of kHz to 1MHz single photoelectron equivalent), thus typically requiring operation in an stable lower temperature environment ($\sim -20°C - 0°C$),
- Large temperature dependence of breakdown voltage (and thus gain at fixed voltage),
- Large crosstalk ($\sim 10\%$) due to photons produced during the avalanche multiplication process,
- Afterpulsing due to charge trapping in the silicon substrate,
- Narrow operating range for Geiger-mode multiplication (1-2V) and, therefore, large sensitivity of gain to small variations in the bias voltage,
- And for HEP, relatively not radiation hard at the current time.

The disadvantages may either be inconsequential for high light-level applications (noise) or may possibly be mitigated in detector and/or electronics readout design. Thus, there is a growing number of companies and groups producing the devices and improvements are proceeding in their design to reduce crosstalk, noise, and tune the optical response of the devices. The main producer of SiPMs is currently Hamamatsu Corp., but several other companies are beginning to market the devices, e.g. SensL, Amplification Technologies, Zecotek, RMD. Government funded groups also are producing SiPMs in useful quantities such as IRST (now FBK) in Trento, Italy and Max Planck Institute in Germany in collaboration with MEPhI in Moscow, Russia.

3. Summary of Review Committee Observations

We begin with some overall observations by the review committee and then address the specific questions of the charge given to the committee.

The committee as a whole viewed the research work being done at Fermilab on SiPMs as extensive, well done, and useful. The speakers conveyed their enthusiasm for the work to the committee. Because the technology has been available for less than a decade, the efforts by Para, Ronzhin, and their collaborators to gain a detailed understanding of the operational characteristics of the devices and the capability limitations are well motivated. Manufacturers of SiPMs have shown interest in the results of these characterization measurements. The work being done for CMS to replace the hadron calorimeter hybrid photodetectors with SiPMs is well focused. The needs for CMS are somewhat at variance with the characterization work. Specifically, CMS immediate needs are to develop production quantity evaluation for the 3000 IRST SiPMs for the outer hadron tailcatcher and provide a viable calibration system. Longer term is the need to understand the radiation (non-)hardness of SiPMs and to develop a plan for dealing with the higher noise induced in rad-damaged SiPMs. The work described by Gene Fisk towards incorporating SiPMs into muon detection is at an early stage. There appears to be a rough plan for this R&D for the next several years: some costing done, plans for MTest work with "Rubinov" digitizers, obtain larger quantities of SiPMs and develop a calibration method using noise pulses. The dual calorimetry work described by Adam Para while advocating use of SiPMs for readout appears to be concentrating on the study and evaluation of candidate crystalline materials. Paul Rubinov made a convincing case that the long term plan for SiPM readout should take advantage of the inherent digital nature of the SiPMs (one photon "fires" one pixel giving a standard signal output). He noted though that integrating SiPMs into an ASIC readout will be a multi-year effort and the needs for the immediate future require treating SiPM signals as analog input to a fast digitizer (QIEs, flash ADCs).

The concerns that the review committee has with the SiPM R&D program at Fermilab are the overall lack of communication and coordination between the groups doing the various research projects, and the need for a more detailed plan for the future of the program. No speaker provided much detail on funding, effort, and technical resource requirements for any of the programs although CMS does seem to have a vision of how this effort will proceed over the next two-plus years for phase one of the SiPM installation in the HCAL.

We turn now to the specific questions given in the charge to the committee.

- **What is the R&D you are doing and why should it be supported?** The committee all agreed that the speakers presented their programs and results clearly.

The general thinking of the committee though was that a justification for supporting the research was somewhat lacking. This is not to say that a strong case for the research cannot be made. The technology is new and has the potential to be of benefit to Fermilab and HEP in general. What is needed is a plan for a coordinated program of research and an identification of the anticipated specific benefits to Fermilab. The committee did feel that the CMS related work has ample justification and should be supported by the lab.

- **What are the prospects for its use in future detectors?** CMS clearly will be using SiPMs in the immediate and longer term future. SiPMs have the potential to replace conventional PMTs for many HEP applications. Gene Fisk noted that the small size of the detectors allows them to be attached directly to scintillator which would eliminate the need for optical fibers and potentially reduce costs. Future prospects depend on determining the feasibility of using SiPMs in moderate or high radiation environments; whether noise, crosstalk, afterpulsing and temperature sensitivity can be mitigated in SiPM fabrication or detector design; the feasibility of integration with readout electronics; and ultimately on whether the unit price can be reduced to the range of a few tens of dollars.

- **What is the current status?** All speakers adequately addressed this question. In general, characterization work has been and is still being done. Timing resolution measurements have been made in MTest and future time-of-flight work is planned for there. CMS has built 4 of the modular arrays of 18 SiPMs that will replace HPDs for the outer HCAL. The plan is to install them at CMS in May, 2009. Currently, SiPM readout is via existing electronics or, for the case of CMS, will be via QIE10. The results of the 3D electronics ASIC fabrication will impact plans for future attempts to integrate SiPMs with an ASIC readout package.

- **What is the plan for the next year?** The CMS program is specified for the next year: begin replacing the HPDs in the outer HCAL with SiPMs and provide for a production quantity evaluation facility at Fermilab. Anatoly Ronzhin's time-of-flight work will continue and have the goal of providing a capability at MTest. The muon program plans to do measurements at MTest. The characterization program is less specific. There is a desire to broaden the scope of the program to study photon detection efficiency, spectral response, long term stability, and radiation hardness. The time scale for this program is somewhat unclear, but it is anticipated that progress will be forthcoming during the next year.

- **Where could this lead, on the ∼five year time scale, or in what experiment?** Other than the CMS program which will address the barrel and endcap hadron

calorimeter readouts during the next several years, no clear vision was provided. This is not unexpected though since much of the current work is directed toward determining the feasibility of using SiPMs in HEP detectors.

- **At what point would this transition to detector specific or project work?** Again for CMS this path is fairly clear. This is already a detector specific application and work is proceeding to make that a reality. For the other SiPM R&D projects there were no stated prospects for specific detector applications.

- **What is the level of financial and personnel resources needed for the next year and longer term?** None of the presentations really addressed this question in any detail. The committee did not get a sense of the personnel resources needed even for the immediate needs of the CMS project.

4. Recommendations

Based on the above observations, the review committee has the following recommendation for the silicon photomultiplier R&D program:

1. The most urgent need for the program is that it be organized into a coherent whole. The various groups should come together to plan a coordinated R&D effort and set some overall goals for the program. It is necessary to make a determination of the personnel resources needed and to determine to what extent a common effort can be used throughout the program. Another aspect of the program coordination should be to provide a means for involvement of new experimental groups into the program. This would provide a path to new detector specific applications (c.f. recommendation #4) and allow new groups to take advantage of the existing infrastructure and expertise. Funding profiles for both the immediate and longer ($\sim$ 5 year) term futures should be formulated. This effort should help in securing both the needed funding and give greater access to technical resources for the R&D program.

2. The CMS upgrade project should receive the highest priority for support within this R&D program.

3. Along a similar vein as the previous recommendation, there should be an effort to utilize Adam Para's characterization setup for doing the production evaluation work for the CMS upgrade. It would be useful for the characterization work to proceed but this resource needs to be utilized to support the lab's work for CMS.

4. Some detector specific future possible applications should be identified. In addition to CMS, some possible examples are Mu2e, SiD, ILD, and liquid argon Dark Matter.

5. An effort should be initiated to integrate SiPMs with electronics and readout. The feasibility of fabricating a complete package of photodetector, bias, thermal stabilization, and readout should be investigated. Integration into (3D) ASICs implies going into the SiPM fabrication business. There was some discussion during the review of interactions with commercial vendors with regard to this integration. Thought should be given to how the lab might best proceed with such a development program.

6. Collaboration with the University of Chicago and Argonne National Laboratory should be encouraged. The existing consortium of these three entities would be a viable way of generating funding and effort for the program. [Disclosure: R. Wagner who chaired this review is involved in SiPM work at Argonne].

7. It may be useful to determine if non-HEP applications such as medical imaging might benefit from work done at Fermilab.

The review committee extends its thanks to the speakers for presenting informative and interesting talks, and to Marcel Demarteau for organizing the review. We appreciate the time and effort that Adam, Anatoly, Jim, Gene, Paul, and Marcel put into the program presented.

A. Charge to the SiPM R&D Review Committee

R&D for HEP experiments in the US will have high priority for the next 5-10 years as we work to define the next generations of experiments that will push the boundaries of our knowledge in the energy, intensity, and cosmic frontiers. To that end, Fermilab needs to have a well focused program of detector R&D so that the directions taken are appropriate, understood, and supported. PPD is planning a series of mini-workshops to review the status, progress, and prospects for all known R&D efforts in the division. For your R&D, we would like to have a series of talks covering:

- What is the R&D you are doing and why should it be supported?
- What are the prospects for its use in future detectors?
- What is the current status?
- What is the plan for the next year?
- Where could this lead, on the ∼five year time scale, or in what experiment?
- At what point would this transition to detector specific or project work?
- What is the level of financial and personnel resources needed for the next year and longer term?

Our plan is to have a half-day mini-workshop whose outcome is a short report to the Division head covering the above questions. Please suggest an agenda with 2-3 hours of talks, including breaks, which address the above questions.

Marcel Demarteau and Bruce Baller will chair the workshop, and will invite several people who have expertise and interest in this area of research to attend who will contribute to the report. The workshop will be open to interested scientists at the lab and user community as well. Your research efforts are vital to the labs future, and we look forward to a very interesting and productive workshop.