Continuing Studies of Geiger-Mode Avalanche Photodiodes for Linear Collider Detector Muon System Readout: *Status Report and 2nd Year Continuation*

Classification

Linear Collider Detector Muon System Readout

Institution and Personnel requesting Funding

Colorado State University
Robert J. Wilson, Professor
David W. Warner, Engineer

Wilson and Warner have worked with photodetectors for many years at various levels including for: the SLD experiment Cerenkov Ring Imaging Device (CRID); BaBar Detector of Internally Reflected Cherenkov light (DIRC); Pierre Auger Observatory; GPD applications for detection of Cerenkov and scintillation light.

Collaborators

Stefan Vasile; President, aPeak Inc.
Scintillator Based Muon Detector Collaboration (E. Fisk, P. Karchin et al.)
Tail Catcher / Muon Tracker Collaboration (V. Zutshi et al.)

Project Leader

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Project Overview

Continuation Summary In this document we present a status report of our investigation of Geiger-mode Avalanche Photodiodes (GPDs) as a potential readout for a scintillator-based muon system, with potential applications to other Linear Collider Detector (LCD) systems. The majority of funds for the investigation are provided by a sub-contract from aPeak Inc., but this work was supplemented by $13,500 awarded in 2005 as a result of the International Linear Collider University-based Linear Collider Detector R&D (LCRD) initiative. These funds have allowed the group to ensure that the substantial industry R&D project is more tightly coupled to the requirements of Linear Colliders detectors. Collaboration with aPeak Inc. through this LCRD project allows the investigator formal access to the proprietary devices and evaluation results being performed under the SBIR sub-contract. Release of this information at LC meetings and workshops is negotiated with the company on a case by case basis to protect their intellectual property rights, but our experience in this regard has been good in each of the past two years of the collaboration.

In the remainder of this section we provide a short overview of the project to provide a context for the status report that follows.

Wavelength Shifting (WLS) fiber readout of scintillator strips remains the primary candidate for at least one US Linear Collider Detector (LCD) concept. Indeed, two proposals to continue developing this technology for LCD applications are being submitted in response to this solicitation. These proposals envision using multi-anode PMTs and SiPM/MRS photodetectors for fiber readout. Multi-anode PMTs are an improvement over traditional single-anode PMTs for this application, but they are still expensive, in large part due to the need for relatively sophisticated electronic readout with amplification, as well as high-voltage supply requirements. We believe this is sufficient motivation for further investigation of alternative photodetectors.

Geiger-mode Avalanche Photodiodes (GPDs) are an interesting candidate photodetector to replace PMT read-out of WLS fibers. We have been working together with aPeak Inc., a small firm in the Boston area that develops novel photodetector devices, to contribute to the development of GPDs specifically for this application. GPDs have several features that are important for these types of applications: relatively high detection efficiency at typical WLS light wavelengths (compared to typical PMTs); high gain; acceptably low dark count rates (for gated operation) with modest cooling; low sensitivity to magnetic fields; and greatly simplified readout electronics, supply voltage requirements, and cable plant. The GPD is intrinsically a digital device, but a certain degree of photon-counting capability could be achieved by multi-pixel readout of each fiber (similar to the principal of the Si-PM) - such a configuration could be self-triggering by incorporating multiplicity logic in the readout.

GPDs have generated significant interest in the HEP community over the past year. Presentations were made at the Snowmass conference detailing the operation of prototype Hamamatsu GPD-based photodetectors, sometimes generically referred to as “Silicon PMTs (SiPM).” The Hamamatsu devices are being considered for use by the T2K neutrino oscillation collaboration (which includes some of the CSU group). Testing of SiPMs produced by a Russian group will continue at Northern Illinois Univ and other locations for possible use in muon system and calorimeter readout systems. These devices consist of large (~1000 pixel per 1mm diameter fiber) arrays of very small (less than 50μm diameter) GPD pixels, with outputs summed to approximate an analog readout of the photon flux. The aPeak approach is to simplify these devices as far as possible, using much smaller numbers of much larger pixels (~16 square pixels ~165 μm per side per fiber) to reduce complexity and provide a high rate, low cost photodetector option for detectors that need only binary (hit/no-hit) information, or photon counting ability over a modest range. The aPeak device has the potential advantage of even lower operating voltage them the other similar devices, around 14 V, rather than above 100 V (other advantages include high volume manufacturing and process repeatability due to the use of industry standard processes). Preliminary results were presented by Wilson at the 2005 ILC Physics and Detector Workshop (Snowmass, Colorado) and Stefan Vasile (aPeak Inc.) at the IEEE Nuclear Science Symposium, Rome 2004.

A combination of the GPD features could reduce the system cost considerably. Geiger-mode devices produce volt-size signals that do not need a preamplifier and the simple active quench circuit required could be done on-chip, providing a digital output. The low voltage power supply and cabling cost should be somewhat lower than for a PMT HV system. Insensitivity to magnetic fields and small size would allow the photodetector to be close to the active detector region, which could reduce the optical fiber plant considerably, resulting in a robust, compact, and relatively inexpensive readout system.

This proposal is a continuation of our 2004 proposal for research into Geiger-mode Avalanche Photodiodes applications that was partially funded as part of the LCRD program last year; we received a small ($13,500), but beneficial, component of that proposal (the funds were received only in October of this year). These funds allowed us to integrate our system with the muon system test bed. The previous year, we received modest but essential LCRD program funding ($15,000) that allowed us to develop temperature control hardware and software to control GPD operating temperatures and study the impact of this control on dark count rate and detection efficiency. This system is used extensively in the current and proposed stages of this project.

In addition to the LCRD funding, in 2004 we completed a successful separate R&D program funded by a Phase I SBIR (Small Business Innovative Research) R&D award to aPeak Inc. The results from this research were sufficiently interesting that aPeak was granted a Phase II award of $735,000 to continue this research, with a subcontract to CSU of approximately $170,000 over two years. A great deal of critical research on GPD performance is supported by this SBIR funding, but it is essential that LCRD funding continue to allow us to interface with the LCRD muon group. In particular we wish to:

- continue participation in the design and planning of the muon system test beds to ensure compatibility with the GPDs (Year 1);
- optimize our GPD fiber readout system using the experience from the SBIR-funded research and in the LCD muon system test bed (Year 2).

Status Report

A combination of LCRD and aPeak SBIR funding allowed us to develop a LabVIEW based computer controlled temperature control system to regulate the temperature of the GPD junctions to approximately +/- 1 degree Celsius (see Fig. 1, Fig. 2).

The temperature control was achieved by monitoring the temperature of the GPD case with a thermocouple and using this as feedback to control the current supplied to a Peltier junction cooling system. The analog readout and current control was provided by a LabJack U12 DAQ system, controlled and monitored via a LabVIEW routine developed and tested at CSU. Data from this temperature control system was integrated directly into our GPD data collection system, allowing us to monitor the GPD temperature on an event-by-event basis.

Measurements of prototype GPD pixels from aPeak have been conducted on a test bed developed here at CSU, and show a clear dependence on temperature of both dark count rate (DCR) and detection efficiency (DE) for cosmic ray events (see figures 3, 4). We observe DCR reductions of a factor of three to four and single pixel detection efficiencies in the range approaching 20%. These are the first such measurements on the aPeak devices.

Significant progress has been made at aPeak (funded by the SBIR) towards producing a 64-fiber readout GPD device. Indeed, an initial prototype device has been fabricated (Fig. 5) and the functionality has been validated at aPeak Inc; testing with triggered light sources and cosmic rays will begin early next year at CSU.

Testing of this device in an LCD muon system test bed is listed as one of the primary goals and justifications for the SBIR award. We have received funding as part of that award to develop the hardware and software necessary to make these tests; the necessary EDIA and travel for this work is being funded by the LCRD grant we received in October 2005 and the funds that we request from LCRD in 2006 and 2007. Work has begun on the design of an optical coupling transition allowing us to read out fiber bundles from the muon system test bed.

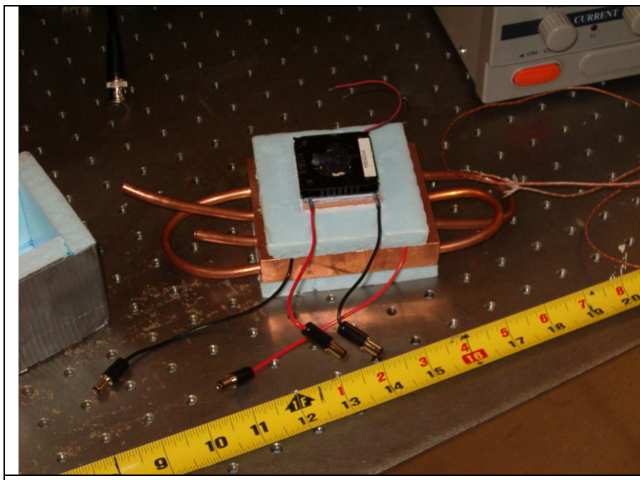

Fig. 1A: Peltier junction cooling device inside

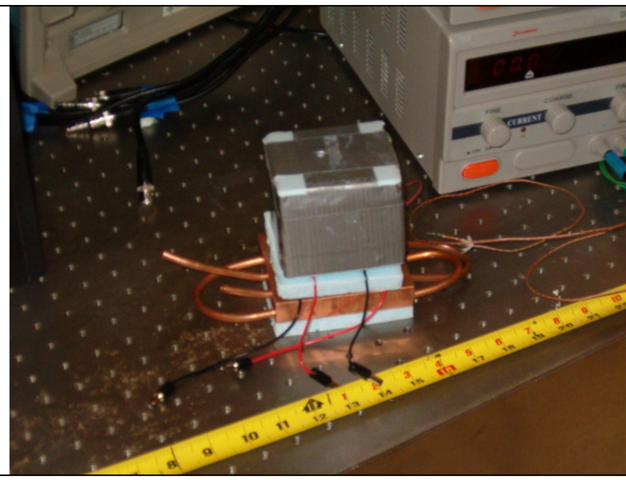

Fig. 1B: Peltier junction cooling device closed

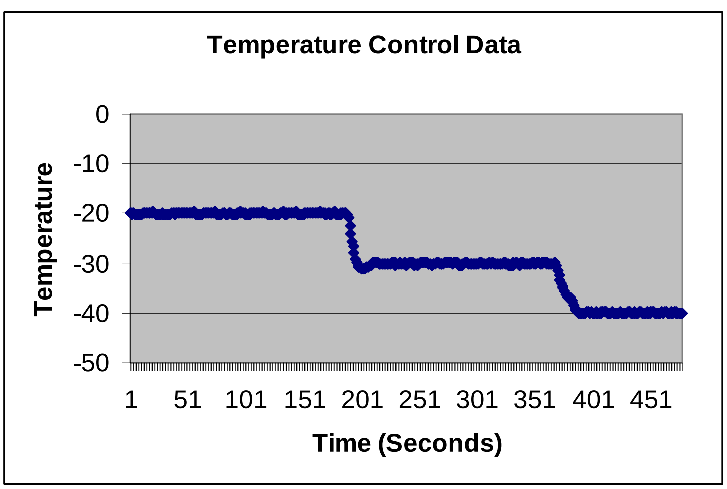

Fig. 2: Temperature stability as a function of time for -20, -30 and -40 degrees Celsius, as measured by a thermocouple mounted to the GPD case.

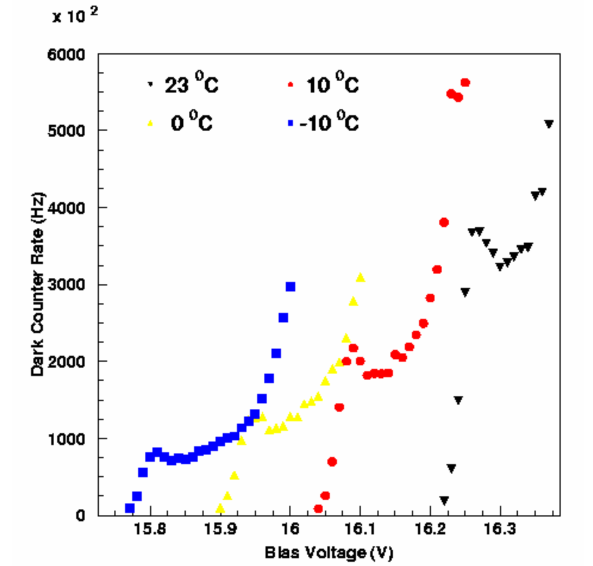

Fig. 3A: Variation in dark count rate as a function of bias voltage at different temperatures

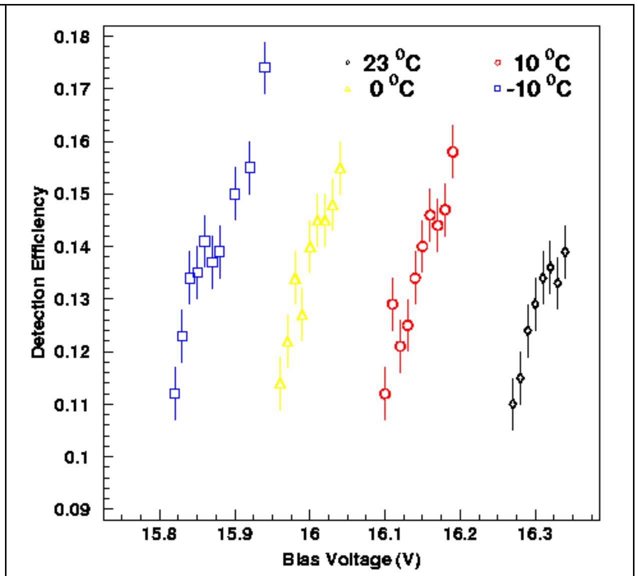

Fig. 3B: Variation in detection efficiency as a function of bias voltage at different temperatures

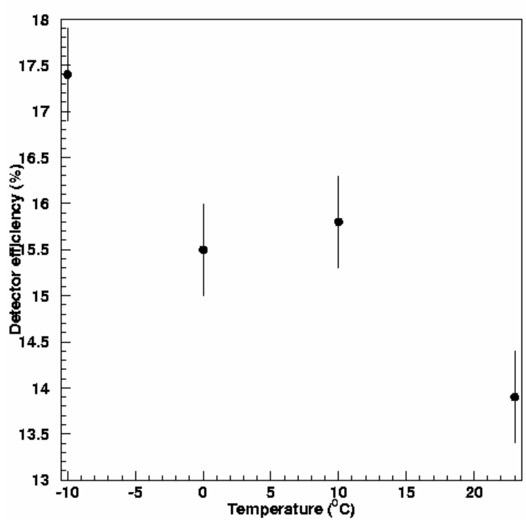

Figure 4: Maximum detection efficiency as a function of temperature.

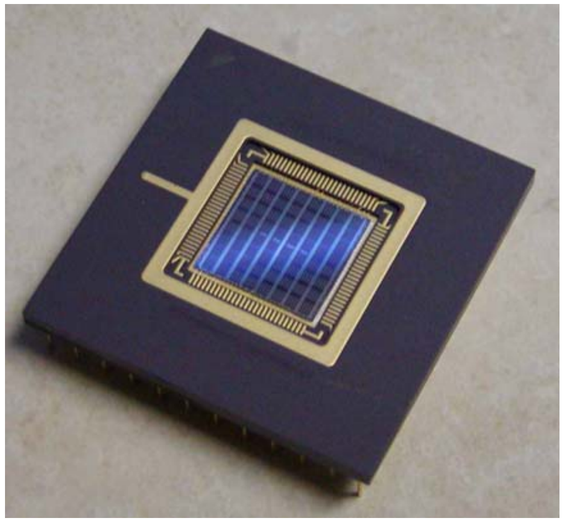

Fig. 5: 64-fiber readout prototype device produced by aPeak Inc. [Proprietary information under the FOIA act.]

Project Activities, Deliverables, and Budgets

We present our proposed activities, deliverables, and budgets below in two sections: a minimal proposal, which assumes funding at the level awarded as a result of last years' proposal, and an optimal version, which allows us to expand the scope of our work to a level that takes better advantage of the opportunities presented by the SBIR funds. These funds will be enhanced also by an internal Academic Enhancement Program (AEP) award from Colorado State University. This award is to expand our High Energy Group photodetector applications research lab, so that we can test and compare a wider range of devices for LCD system readout. For example, during the next few months we will acquire an MAPMT and readout electronics using these funds. Our ultimate goal is to work with the muon system group on whichever photodetector system is demonstrated to be the optimal choice for the experiment.

2006 Project Activities and Deliverables

Testing of the GPDs in the LCD muon system test bed is scheduled for the mid-2006. LCRD funding from 2006 will allow us to interface with the LCD muon system team to ensure a smooth mechanical interface between the GPD array and the test bed fiber bundle, and also to develop the interfaces necessary to allow us to read out the GPD array signals as part of the muon system test bed electronics. This will allow a direct comparison between GPD performance and that achievable with other photodetector technologies.

The additional funding requested beyond the previously-awarded funds will allow us to support a second-year graduate student for the summer to participate in the data analysis of GPD data, as well as additional personnel and travel funds to support a trip to an ILC meeting and a summer conference (ILC workshop, such as Snowmass '05), to present results from our GPD research. These additional funds will leverage the AEP award from the University for a photodetector research lab to serve the needs of the ILC community. Our goal is to increase our overall involvement in ILC photodetector research. This activity would also contribute to the development of detectors required for specialized hadron identification systems if such is desired.

2007 Project Activities and Deliverables

In 2007 we will analyze the data collected in the 2006 test beam run. Using this information, we will design an improved GPD-based system with the goal of developing a proposal for a high-reliability, cost effective GPD-based readout system for use in LCD muon system readout.

Additional funding requested beyond the existing LCRD program will allow us to involve a second-year graduate student in the muon system program, assisting us either to integrate the GPDs into the muon system readout system software and electronics hardware and/or to take advantage of the funding available through the AEP to further our involvement in ILC photo detector applications.

Budget Justification

Year 1:

Integration of the GPD array prototypes into the ILC test bed will require cooperation with the muon detector group, largely centered in close proximity to Fermi National Accelerator Lab. A continuation of the current level of funding (Table 1) would provide funds to cover approximately 152 hours of EDIA (at the Technical Design Facility rate of $53 per hour) and two 2-day trips (@ $600 each) to the Chicago area for coordination of this effort. This modest level of support would allow us to sustain a basic presence and linkage between the aPeak development and LCD.

A modest additional level of support (Table 2) would take far better advantage of the SBIR and university funds. It extends the minimal support with: summer salary for a non-resident graduate student (Rey Nann Ducay – who has 5 months experience working with the devices in our lab); purchase of enough WLS and clear fiber ($4150) machined and polished at FNAL ($2,000) to built a small 64-fiber test bed at CSU (currently we have only 8 fibers); a trip an international ILC workshop/conference to report on progress/ results ($1200); additional travel ($800) to bring the aPeak designer (Stefan Vasile) to a LC workshop to present technical data about the device (this small business does not have funds to provide this themselves); and an additional 48 hours of EDIA support to increase technical support of the ILC muon detector project, particularly for integration of both GPD and MAPMT readouts.

Year 2:

Following testing in the ILC muon system test bed, the GPD array readout concept will need to be revised and developed for potentially larger scale systems. Designs for electronics and mounting schemes demonstrating feasibility of the GPD concept will be required. The same level of continuation funding as this year would provide approximately 157 hours of EDIA (at the projected Technical Design Facility rate of $55/hour) but only a single 2-day trip to the Chicago area to begin development of an initial muon system readout utilizing GPD arrays.

Optimal support would provide also: salary for a senior non-resident graduate student for a full year to participate in the full system testing and analysis; additional trips to FNAL and an international ILC workshop/conference; and additional EDIA (200 hours total) to allow greater involvement of our technical personnel in the ILC muon detector project; an estimate for M&S of $7,500 is based on past experience for such items as cables, mounting prototype and fabrication, other supplies needed for a beam test. More detailed budget would be provided in the next continuation proposal.

Table 1: Budget – FY05 Level

Item	Year 1	Year 2	Total
Other Professionals*	$ 8,047	$ 8,647	$ 16,693
Graduate Students	-	-	-
Undergraduate Students	-	-	-
Total Salaries & Wages	**8,047**	**8,647**	**16,693**
Fringe Benefits (grad. student only @ 3.6%)	-	-	-
Total Salaries, Wages & Fringe Benefits	**8,047**	**8,647**	**16,693**
Equipment	$0	$0	$0
Travel	1,200	600	1,800
Materials & Supplies	-	-	-
Other Direct Costs	-	-	-
Total Direct Costs	**9,247**	**9,247**	**18,493**
Indirect Costs (46%)	4,253	4,253	8,507
Total Direct & Indirect Costs	**$13,500**	**$13,500**	**$27,000**

Table 2: Budget Request

Item	Year 1	Year 2	Total
Other Professionals*	$10,600	$11,000	$21,600
Graduate Students	$4,560	$18,240	$22,800
Undergraduate Students	$0	$0	$0
Total Salaries & Wages	**$15,160**	**$29,240**	**$44,400**
Fringe Benefits* (grad. student only @ 3.6%)	$164	$657	$821
Total Salaries, Wages & Fringe Benefits	**$15,324**	**$29,897**	**$45,221**
Tuition	-	$1,958	$1,958
Equipment	-	-	-
Travel	$3,200	$2,400	$5,600
Materials & Supplies	$6,150	$7,500	$13,650
Other Direct Costs	-	-	-
Total Direct Costs	**$24,674**	**$41,755**	**$66,429**
Indirect Costs (46% on TDC excl. tuition)	$11,350	$18,307	$29,657
Total Direct & Indirect Costs	**$36,024**	**$60,062**	**$96,086**

* EDIA is billed at an hourly rate so fringe benefits are not provided explicitly. The fringe benefit rate for engineers in this facility is 20.3%.