Muon System and Particle Identification

Muon System and Particle Identification Table of Contents

Introduction to Muon System R&D

The identification and precise measurement of muons is critical to the physics program of the linear collider. The muons produced from decays of W and Z bosons and from B-hadrons are key parts of the signatures for the Higgs and hypothesized new particles. Muons may also be produced directly from decays of new particles such as supersymmetric scalar muons.

The linear collider detector design includes a sub-system that will identify muons, as distinct from hadrons, primarily by their penetration through the iron flux return. This muon system should operate over the widest possible momentum range with high efficiency for muons and low contamination from pions. In addition, it may be used to measure the leakage of hadronic showers from the calorimeter and hence improve the energy resolution of hadronic jets.

Because the muon system is the largest one in the LC detector, it is important that a realizable design, verified by prototyping, is established early, so that an optimal detector is delivered on time and within budget. The muon system must maintain stable operation with high reliability since the detectors are largely inaccessible. These are challenging requirements for operation over a span of perhaps 20 years.

Two sub-proposals, A and B, are submitted using alternating layers of scintillator and steel as active and passive media. Both proposals are from the same collaboration, only the funding sources are different. Proposal C studies the use of avalanche photodiodes as a possible readout technology.

A.	LCRD 7.2	Scintillator Based Muon System R&D 2004-2007	H. Eugene Fisk Paul Karchin	Fermilab Wayne State
B.	UCLC 7.3	Scintillator Based Muon System R&D	Arthur Maciel Mitchell Wayne	NIU Notre Dame
C.	LCRD 7.5	Demonstration of Geiger Mode Avalanche Photodiodes for Linear Collider Muon System Readout	Robert Wilson	Colorado State

7.2. Scintillator Based Muon System R&D 2004-2007 (LCRD)

Muon system and Particle ID

Contact person: Paul Karchin
email: karchin@physics.wayne.edu
phone: (313) 577-5424

UC Davis
Fermilab
Northern Illinois
Notre Dame
Rice
Wayne State
UT Austin

Year 1: 76288
Year 2: 91372
Year 3: 92889

Project Name: Scintillator Based Muon System R&D 2004-2007

Classification (accelerator/detector:subsystem) Detector: Muon

Institution(s) and personnel

Fermilab, Batavia, Illinois: Alan Bross, H. Eugene Fisk (Co-contact Person), Kurt Krempetz, Caroline Milstene, Adam Para, Oleg Prokofiev, Ray Stefanski

Northern Illinois University, DeKalb, Illinois: Gerald Blazey, Dhiman Chakraborty, Alexandre Dychkant, David Hedin, Arthur Maciel

Notre Dame University, South Bend, Indiana: Mitchell Wayne

Rice University, Houston, Texas: P. Padley, M. Matveev, J. Roberts

University of California, Davis, California: Mani Tripathi, Richard Breedon

University of Texas, Austin, Texas: Karol Lang

Wayne State University, Detroit, Michigan: Alfredo Gutierrez, Paul Karchin (Co-contact Person)

Contact persons

H. Eugene Fisk
hefisk@fnal.gov
(630) 840-4095

Paul E. Karchin
karchin@physics.wayne.edu
(313) 577-5424

Introduction

We propose a three year research program to design and test a prototype muon detector for the linear collider detector. The identification and precise measurement of muons is critical to the physics program of the linear collider. The muons produced from decays of W and Z bosons provide key signatures for the Higgs and possible new particles. Muons may also be produced directly from decays of new particles.

The linear collider detector design includes a muon system that will identify muons, as distinct from hadrons, primarily by their penetration through the iron flux return. The muon system should operate over the widest possible momentum range with high efficiency for muons and low contamination from pions. Because the proposed calorimeters are thin in terms of interaction lengths, hadronic showers will leak into the muon steel. With an adequately designed and proven muon system, it may be possible to measure the leakage and hence improve the energy resolution of hadronic jets. The muon system must maintain stable operation with high reliability since the detectors are largely inaccessible. These are challenging requirements for operation over a span of perhaps 20 years.

A promising design for the muon system is suggested by the successful operation of scintillator and iron calorimeters used in neutrino experiments, such as CDHS, to measure the energy of jets. For example, with 10 cm of Fe between counters, hadronic resolutions of ~0.8/sqrt(E) are typically achieved. A scintillator strip calorimeter based on MINOS style detectors may provide the resolution required for a useful measurement of shower leakage.

For the muon system we propose for the linear collider, the general layout of the barrel muon detectors consists of planes of scintillator strips inserted in gaps between 10 cm thick Fe plates that make up octagonal barrels concentric with the e^+e^- beamline. The scintillator strips, ~5 cm wide and 1 cm thick, contain one or more ~1 mm diameter wavelength shifting (WLS) fibers. Light produced by a charged particle is transported via clear fibers to multi-anode photomultipliers located outside the Fe yoke where it is converted to an electronic signal. There are 14 planes of scintillator with alternating strips oriented at $\pm 45^o$ with respect to a projection of the beam line onto the planes.

We propose to optimize the design of a scintillator-based muon system with a coordinated program of simulation studies and performance measurements of prototype detectors. The simulation studies will include development of software that is integrated into the world-wide LC framework. The software will support different geometry descriptions, parametric variation of geometries and will have a user friendly interface. We will develop techniques to produce the components of a prototype system: iron absorber plates and mechanical support, extruded scintillator strips embedded with wavelength shifting optical fibers, splicing and routing of fibers and their interface to multi-anode photomultiplier tubes and readout electronics. In the first year, several prototype planes and readout will be produced. In the second year, the prototype system (including absorber) will be tested with cosmic rays. In the final year, a system of 8 planes and absorber will be operated in a test beam. Because the muon system is the largest one in the LC detector, it is very important that a realizable design, verified by prototyping, is established early, so that a well-working detector is delivered on time and within budget.

Progress report for FY2003

Summary progress reports from each institution are given below. For each activity, a web address is given where a more detailed report is available. The work at Fermilab was funded as part of the Fermilab budget. LCRD grants were awarded to UC Davis and Wayne State in July. UCLC planning grants were awarded to NIU and Notre Dame in August. UT Austin provided consulting help and loaned us two MINOS prototype MAPMT's with bases.

Software Development

<u>Contributions to the global software effort</u> (Arthur Maciel - NIU)

The NIU group has joined a worldwide effort to develop a universal simulation software framework. The main goal is the specification of detector geometry by software that will “plug in” to the simulation engine. This approach will minimize overlapping efforts, enable direct performance comparisons, encourage sharing of detector representations and allow swapping of sub-detectors through standardized simulation tools, objects, and formats. The early development of the framework has been associated with tracker and calorimeter modules. Because there was no detailed simulation of the U.S. proposed muon system, the NIU group has proposed to the NSF (UCLC) the development of an LCD μSim-compatible muon system representation.

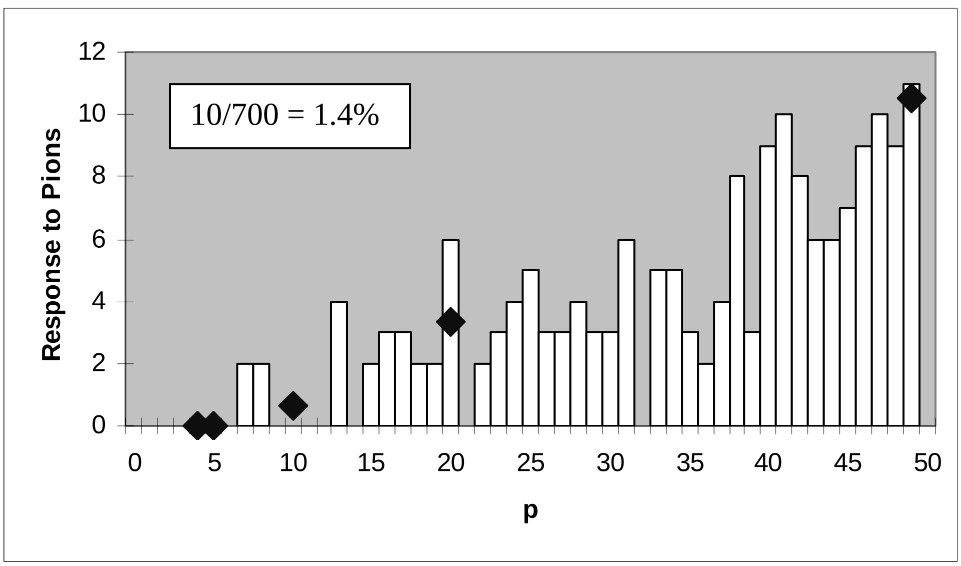
The first steps towards “μSim” are the prototype development by the NIU group that allows planar detector geometries, as distinguished from the existing cylindrical geometry. The software consists of a stand-alone C++ package, with the option to couple to ROOT, in which the representation of a single track is available as a (θ,φ) coordinate pair or a (u,v) pair. This will allow us to study MAPMT channel multiplexing schemes, dependence of muon tracking on scintillator strip layout, widths and stereo angles, ambiguity resolving schemes, parameter optimization, etc.

Further discussion of the NIU prototype software can be found at: http://www-d0.fnal.gov/~maciel/LCD/awg_lcdmu.html.

Contributions to the analysis software effort (Caroline Milstene – Fermilab/NIU)

There has been significant progress in the analysis of Monte Carlo generated events with regard to three topics: muon detector tracking and identification algorithms, tracking efficiency, and hadron punch-through probability. The analysis software development has been done using the SLAC software package: Java Analysis Studio (JAS) and an initial muon tracking Java package developed by Rich Markelov. The Silicon Detector (SD) events that have been analyzed were GEANT3 output samples of single muons and pions. The momenta chosen for each of the 5000 event singles samples were fixed at 2, 3, 4, 5, 10, 20 and 50 GeV/c.

The muon identification algorithm looks for single hits in the muon detectors that are located between 2" thick "cylindrical" Fe solenoid flux return plates. Charged tracks that have been generated upstream of the muon detectors are projected into the muon system and a (θ,φ) match is required for the muon candidate track that is consistent with multiple scattering and energy loss. A plot of efficiency vs. muon momentum shows the efficiency reaches 95% at 4 GeV/c and that it is 99% at 10 GeV/c. The low-momentum efficiency has been increased by including dE/dx in the (θ,φ) matching. This work is an extension of earlier studies carried out by Marcello Piccolo.



In similar fashion, punch-through has been studied for pions with the same momenta as given above. The analysis results of M. Piccolo are also shown (solid histogram), adjusted for the differences between the TESLA and SD detectors. The punch-through probability is given by dividing by 700, the relative normalization constant per momentum bin for the two analyses. Additional studies are in progress to see if inclusion of hadronic and electromagnetic calorimeter information in the analysis can reduce punch-through.

Present studies are focused on b-pair production where there is at least one muon in the final state. The object is to understand punch-through and identification efficiencies in the midst of jet backgrounds. Further info is available at: http://homefnal.gov/~caroline.

Hardware

Scintillator/Module Design (A. Bross/G. Fisk/K. Krempetz/A. Para – Fermilab)

Work has progressed on the design of 2.5 m by 5.0 m strip scintillator planes. There are the equivalent of 86 strips, with dimensions 4.1 cm wide by 1 cm thick by 3.5 m long, laid adjacent to each other as shown below. The strip scintillator is of the MINOS type (same specification). Requisitions for POPOP, scintillator and fiber (both wavelength shifting and clear) to build seven planes have been submitted. The order for 1.2 mm diameter fiber with 4.5 km of WLS type and 3 km of clear was placed with Kuraray on September 30, 2003. The cost of these orders is approximately: $27.4K for fiber, $4.6K for POPOP and $7.1K for scintillator bars.

Fiber R&D (Mitch Wayne – Notre Dame Univ.)

A first pass design of fiber routes has been made. A drawing for the fiber routes that take into account the splices and bends in he fibers has been made. Splicing of WLS and clear fibers has been done, but the light transmission has not yet been measured. Drafting prints of the various drawings are available at: http://www-d0.fnal.gov/~maciel/LCD/awg_lcdmu.html.

MAPMT Testing and Calibration (Alfredo Gutierrez, Engineer; Rajesh Medipalli, Graduate Student; Paul Karchin – Wayne State Univ.)

The WSU group learned to operate a Hamamatsu PMT with 16 anodes mounted in an assembly used by the MINOS experiment that provides HV biasing and anode routing to mass termination cables. A 16-hole aluminum block was fabricated to route fibers onto the pmt photocathode face. Digital oscilloscope waveforms were recorded of the pmt response to a pulsed, red light emitting diode coupled via a clear optical fiber to the pmt cathode. The charge response of a LeCroy QVT multichannel analyzer was calibrated using a pulse generator and digital oscilloscope, in preparation for absolute charge measurements of pmt pulses. Work on recording anode charge spectra using the LED source is in progress. More details can be found at http://hep6.physics.wayne.edu/~karchin/lcrd.

Readout R&D (Britt Holbrook, Engineer; Juan Lizarazo, Graduate Student; Mani Tripathi – Univ. of California at Davis)

The UCD group has designed and fabricated a printed circuit board, which houses a 16-channel MAPMT. A dynode biasing network and 16 channels of preamplification are provided on-board. The preamplifiers are "in-line" circuits, i.e., the same co-axial cable is used to power the circuit and to carry away the output signal. This feature will lower the burden on the cabling in any future design. The preamplifier rise-time has been measured to be less than 1 ns and hence, we hope to be able to measure the time of arrival (TOA) of single photoelectrons with a 0.5 ns precision. The signals from the preamplifiers are fed into discriminators, followed by TDCs, both of which are CAMAC units borrowed from PREP at Fermilab. The TDCs are read out using the front-panel ECL bus and fed into an FPGA that also provides trigger and control features. Finally, the data from the FPGA are readout into a Linux computer via the parallel port. For reports in greater detail, see http://ucdcms.ucdavis.edu/electronics/ .

Work to be done and deliverables by Institutes

Institute/ Year	Work	Deliverables
FNAL		
FY04	Establish mechanical infrastructure for module production; begin mechanical and electronics infrastructure for test stand; begin procurement of front-end electronics.	several scintillator modules, initial results on module properties
FY05	Procure fiber; complete electronics infrastructure; continue procurement of front-end electronics; begin construction and stacking of iron absorber; begin preparation of mechanical and electronics infrastructure for test beam.	extensive measurements of module properties, infrastructure ready for cosmic ray measurements, report on performance of pmt readout with preamp boards
FY06	Produce full set of modules with extruded scintillator and embedded fibers; complete procurement of front-end electronics; complete setup of iron absorbers; complete test beam instrumentation.	full set of modules and absorbers, infrastructure ready for beam tests, report on results of cosmic ray tests
NIU		
FY04	Develop C++/GEANT4 description of muon system in context of general LC detector framwork; develop muon tracking algorithm; help commission scintillator extrusion facilty at FNAL; design test stand, develop fiber embedding method.	GEANT4 description of preliminary muon detector and demonstration of muon tracking for simulated events, comparative study of extruded and conventional strips
FY05	Optimize detector parameters from simulation; couple muon detector with tracker and calorimeter; measure light yield and time resolution versus position in strip and parameters of the strip and fiber properties.	simulation results for muon efficiency and fake rates for different muon detector designs including integration with tracker and calorimeter, performsnce measurements for strips of various lengths, widths and fiber placements
FY06	Complete optimization of parameters from simulation; write user friendly interface with documentation; produce a significant number of scintillator modules.	completed muon simulation package integrated into LC detector software framework, report on scintillator mass production techniques, quality control and costs
UCD		
FY04	Design/fabricate a preamplifier board for M64 pmt's; provide TDC readout and control using an FPGA.	4 prototype preamp boards, FPGA readout system and a document with test results
FY05	Design/fabricate a board housing 16 dual channel, 1 GHZ flash ADC's and an FPGA controller.	4 prototype FADC boards and a document with instructions and test results
FY06	Produce balance of readout electronics (with help from Fermilab). Install system at Fermilab.	balance of 1024 channels of preamps and ADC boards installed at Fermilab
UND		
FY04	Devise fiber routing scheme; develop fiber splicing method; procure WLS fibers.	description of routing scheme and spicing method, specification of WLS fibers
FY05	Measure optical properties of WLS and clear fibers; design light guide manifolds.	report on fiber measurement system and results, manifold engineering design
FY06	Produce manifolds for 8 planes - install and test.	completed optical distribution system
WSU		
FY04	Procure 4 pmt's and bases - test and calibrate. Install pmt's with scintillator planes at FNAL.	description of calibration procedure and results., records of pulse height spectra with scintillator
FY05	Develop LED calibration system - test at WSU and FNAL. Procure & calibrate 4 pmt's; install at FNAL.	description of calibration system and performance, response for noise and cosmic rays
FY06	Install calibration system at FNAL test beam. Procure & calibrate final 4 pmts's; install at FNAL.	report on performance of calibration and signal response with test beam data

Three Year Budget

Below we include tables of the proposed budgets for the institutions involved thus far in the LCD Muon R&D effort for the years FY04-FY06. Although Fermilab is not requesting UCLC or LCRD funds from the NSF or DOE, the Fermilab LCD Muon R&D budget is given for reference.

DOE University Budget	***FY2004***		***FY2005***		***FY2006***		***Total***	
Salaries and Wages:	***UCD***	***WSU***	***UCD***	***WSU***	***UCD***	***WSU***	***UCD***	***WSU***
Research Engineer		4,004		4,084		4,166		12,254
Graduate Students	13,428	10,449	15,409	17,847	15,717	18,204	44,554	46,499
Undergraduate Students	3,800		4,000		4,200		12,000	
Total Salaries and Wages	17,228	14,453	19,409	21,931	19,917	22,370	56,554	58,753
Fringe Benefits	517	3,363	527	5,091	538	5,193	1,582	13,647
Equipment	9,000	8,000	8,000	8,000	8,000	8,000	25,000	24,000
Travel	3,000	3,250	3,100	3,250	3,200	3,250	9,300	9,750
Materials and Supplies	2,000	2,000	2,000	2,000	2,000	2,000	6,000	6,000
Tuition & Fees	2,330	2,938	4,753	6,111	4,848	6,356	11,931	15,406
Total Direct Costs	34,075	31,066	37,789	40,272	38,503	40,813	110,367	112,150
Indirect Costs	5,914	5,233	6,509	6,802	6,695	6,879	19,118	18,914
Total Direct and Indirect Costs	39,989	36,299	44,298	47,074	45,198	47,691	129,485	131,064

NSF University Budget	***FY2004***		***FY2005***		***FY2006***		***Total***	
Salaries and Wages:	***NIU***	***UND***	***NIU***	***UND***	***NIU***	***UND***	***NIU***	***UND***
Engineer		7,000		8,000		10,000		25,000
Graduate Students	4,635	3,000	4,774	7,000	4,917	8,000	14,326	18,000
Undergraduate Students	3,000		3,000	2,000	3,000	2,000	9,000	4,000
Total Salaries and Wages	7,635	10,000	7,774	17,000	7,917	20,000	23,326	47,000
Fringe Benefits		1,400		1,600		2,000		5,000
Equipment		9,000		9,000		5,000		23,000
Travel	3,000		3,000		3,000		9,000	
Materials and Supplies	5,300		5,400		5,402		16,102	
Subcontract		20,048		20,349		20,532		60,929
Total Direct Costs	15,935	40,448	16,174	47,949	16,319	47,532	48,428	135,929
Indirect Costs	4,113	15,252	4,175	11,423	4,213	10,670	12,501	37,345
Total Direct and Indirect Costs	20,048	55,700	20,349	59,372	20,532	58,202	60,929	173,274

Fermilab LC Muon System R&D Budget	***FY20004***	***FY2005***	***FY2006***
Module Production, Mechanical: parts, fixtures, etc.	17,800	15,000	43,800
Module Electronics: HV, cables, connectors, FE board production	16,500	20,500	20,000
Test Stand Fabrication, including 40T Fe	3,500	13,000	15,000
Test Equipment	8,500	6,000	6,000
Test Beam		15,000	13,000
Labor			
1 FTE Engineer - Mechanical/Electrical	-	-	-
2 Technicians	-	-	-
2 Coop Students	50,000	50,000	50,000
Total	96,300	119,500	147,800

7.3. Scintillator Based Muon System R&D (UCLC)

Muon system and Particle ID

Contact person: Mitchell Wayne
email: wayne@undhep.hep.nd.edu
phone: (574) 631-8475

NIU
Notre Dame

Year 1: 55700
Year 2: 59372
Year 3: 58202

6 Muon System

6.1 Scintillator Based Muon System R&D

Personnel and Institution(s) requesting funding

Gerald Blazey, Dhiman Chakraborty, Alexandre Dychkant, David Hedin,
Jose G. Lima, Arthur Maciel, Northern Illinois University, DeKalb, IL
Mitchell Wayne, University of Notre Dame, Notre Dame, IN

Collaborators

Alan Bross, H. Eugene Fisk, Kurt Krempetz, Caroline Milstene,
Adam Para, Oleg Prokofiev, Ray Stefanski, Fermilab
Paul Karchin, Wayne State University, Detroit, MI
Mani Tripathi, University of California, Davis, CA

Project Leader

Mitchell Wayne
wayne@undhep.hep.nd.edu
(574)631-8475

Project Overview The linear collider detector design includes a muon system that will identify muons, as distinct from hadrons, primarily by their penetration through the iron flux return. Because the proposed calorimeters are thin in terms of interaction lengths, hadronic showers will leak into the muon steel. The proposed particle-flow algorithms anticipate measuring jet energies by using charged particle momenta, EM shower energies for neutral pions, and hadron calorimetry for neutrons and K_L's. Fluctuations of the neutral hadron energies leaking from the hadron calorimeter will degrade the energy resolution. An adequately designed and proven muon system could be used to measure the ”punch-through” hadron energy escaping the calorimeter and improve the energy resolution of the detector. It is in this context that we propose an R&D program for a scintillator-based muon detection and identification system.

The general layout of the barrel muon detectors consists of planes of scintillator strips inserted in gaps between 10 cm thick Fe plates that make up octagonal barrels concentric with the e+e- beamline. The scintillator strips, with nominal width of 5 cm and 1 cm thickness, will contain one or more 1 mm diameter wavelength shifting (WLS) fibers. The investigation of optimal strip properties and sizes is a part of this project.

Light produced by a charged particle will be transported via clear fibers to multi-anode photomultipliers located outside the Fe yoke where it will be converted to electronic signals. Nominally there are 16 planes of scintillator with alternating strips oriented at 45° with respect to a projection of the beam line onto the planes.

Given a substantial knowledge base from experiments like MINOS, CDHS and others one might ask if an R&D effort on a scintillator-based muon system is necessary. In fact, it is. There are significant differences in the environments for neutrino experiments and the proposed linear colliders. For the LCD, detectors must be robust and ready to withstand 20 years of beam time in a radiation environment. The geometry and packaging of the scintillator detectors are very challenging. There is much in the way of mechanical engineering of the iron, fiber and cable routing, etc. that needs to be determined at an early stage to ensure that important details for the largest LC detector system are not overlooked.

FY2004 Project Activities and Deliverables

NIU Software Development: The first year deliverables will be a preliminary description of the muon subsystem for the overall GEANT4-based simulation of the full detector simulation package, which is described in Project 5.5, *Development of particle-flow algorithms, simulation, and other software for the LC detector*, and a stand-alone muon tracking algorithm.

NIU Hardware Development: joint work with Fermilab for the commissioning of a scintillator extrusion facility. Design of a Test Stand for the Quality Control of extruded scintillator plates. Initial studies of techniques to embed fibers into the muon strips. Deliverables will include the production of extruded scintillator strips and inital measurements of their properties compared to standard methods of producing counters. This will require the manufacture of a die.

UND Hardware Development: Devise a fiber routing scheme. Create a technique for the splicing/joining of WLS and Clear fibers. Decide on the specifications, and order the WLS fibers.

FY2005 Project Activities and Deliverables

NIU Software Development: Continued development of the muon module for the full-detector simulation. Coupling to the other subdetectors. Simulation-based detector optimization. In the second year, we'll carry out extensive simulation-based comparisons between different detector designs. With it, we expect to achieve a solid understanding of the muon system tracking ability, fake rates, and subsystems integration, such as the inter-dependence of parameter choices and the mutual assistance with calorimetry and central tracking for particle ID, particle flow and energy/momentum resolution.

NIU Hardware Development: Measurements of the performance (such as light yield and resultant efficiencies and time resolutions) as a function of parameters such as position along the strip, fiber placement and number of fibers, and counter length. Comparisons will be made between extruded and non-extruded strips. At least one additional size die will be made and prototype strips manufactured.

UND Hardware Development: Quality assurance on WLS and Clear fibers. Design and use a system to measure optical transmission. Engineering design of prototype light guide manifolds.

FY2006 Project Activities and Deliverables

NIU Software Development: Completion of the muon simulation, track reconstruction and analysis software. Completion of all simulation-based studies of detector design characteristics and parameter optimization. The third-year deliverable will be a mature muon-system module for the GEANT4-based full-detector simulation package, muon reconstruction software, results of design optimization studies, and complete documentation.

NIU Hardware Development: Produce a significant number of pre-production prototypes to understand production details, costs, and uniformity. Depending on the needs of other R&D efforts, these counters could then be installed and used in test beams (e.g. calorimeter tests). Deliverables will include the produced counters. Also a third year deliverable (both hardware and software) should be a significant contribution to the muon system TDR.

UND Hardware Development: Production of prototype manifolds for eight planes. Test manifolds, install the manifolds with light guides for the eight planes.

Budget justification

All NIU salaries for professional support staff (including electronics, computing, and machine shop personnel) will be provided by the Department, the State, or other grants. The NIU budget requests support for an undergraduate student through the REU program and for the summer support for a masters graduate student. It is our experience that students at this level are well-matched to the R&D tasks in this proposal. Three NIU undergraduates worked on LC muon related tasks (both simulation and detector R&D) during the Summer of 2002, and this request will aid in continuing student involvement.

The NIU budget requests $5.4K in materials and supplies (such as scintillator, fiber, PMTs) which will be used in the construction of prototype counters. Travel funds of $3K are requested to support international and domestic travel. NIU grant matching funds for the support on LC muon R&D are primarily from the State of Illinois HECA program. This provides the salary for Dychkant, and partial support for Maciel and Hedin. In addition, HECA funds will provide $9K for student support, $15K for equipment and M&S, and $2K for domestic travel. NIU grant matching funds for the support on LC muon R&D are primarily from the State of Illinois' HECA program. This provides the salary for Dychkant, and partial support for Maciel and Hedin. In addition, HECA funds will provide $9K for student support, $15K for equipment and M&S, and $2K for domestic travel.

The University of Notre Dame requests support for the mechanical engineering associated with fibers: routing and layout, optical coupling of clear and WLS fibers, support structures and light-tighting and the mapping of the readout fibers into the multianode photomultiplier tubes. A total of $25,000 over three years is requested for this engineering and associated technical work. The fringe benefit rate applied to this engineering and technical support is 20%. The UND budget also requests support for a graduate and undergraduate student, with 3-year totals of $18,000 and $4,000, respectively. A total of $23,000 is requested for constructed equipment, which includes the cost of the clear waveguide fiber, material and costs for the splicing of wavelength-shifting fiber to clear fiber, and the material and costs of the routing and support structure for the readout fibers. An indirect cost rate of 49% is applied to the engineering and technical costs. This indirect rate is also applied to the first $25,000 of the subaward to NIU.

Three-year budget, in then-year K$: Northern Illinois University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	4.635	4.774	4.917	14.326
Undergraduate Students(REU)	3.000	3.000	3.000	9.000
Total Salaries and Wages	7.635	7.774	7.917	23.326
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	7.635	7.774	7.917	23.326
Equipment	0	0	0	0
Travel	3.000	3.000	3.000	9.000
Materials and Supplies	5.300	5.400	5.402	16.102
Other direct costs	0	0	0	0
Total direct costs	15.935	16.174	16.319	48.428
Indirect costs (*)	4.113	4.175	4.213	12.501
Total direct and indirect costs	20.048	20.349	20.532	60.929

(*)totals: 25% on REU (=K$2.250) and 26% on remainder (=K$10.251)

Three-year budget, in then-year K$: University of Notre Dame

Item	FY2004	FY2005	FY2006	Total
Other Professionals(1)	7.0	8.0	10.0	25.0
Graduate Students	3.0	7.0	8.0	18.0
Undergraduate Students	0	2.0	2.0	4.0
Total Salaries and Wages	10.0	17.0	20.0	47.0
Fringe Benefits(2)	1.4	1.6	2.0	5.0
Total Salaries, Wages and Fringe Benefits	11.4	18.6	22.0	52.0
Equipment	9.0	9.0	5.0	23.0
Travel	0	0	0	0
Materials and Supplies	0	0	0	0
Other direct costs	0	0	0	0
Subcontract	20.048	20.349	20.532	60.929
Total direct costs	40.448	47.949	47.532	135.929
Indirect costs(3)	15.252	11.423	10.670	37.345
Total direct and indirect costs	55.700	59.372	58.202	173.274

(1) Engineering work

(2) 20% of “Other Professionals”.

(3) 48.5% of “MTDC” and “1st $25,000 of Subcontract”.

7.5. Demonstration of Geiger Mode Avalanche Photodiodes for Linear Collider Muon System Readout (LCRD)

Muon system and Particle ID

Contact person: Robert Wilson
email: wilson@lamar.colostate.edu
phone: (970) 491-5033

Colorado State

Year 1: 62200
Year 2: 73700
Year 3: 79900

Demonstration of Geiger Mode Avalanche Photodiodes for Linear Collider Muon System Readout

David Warner, Robert J. Wilson
Colorado State University

Abstract

We propose to demonstrate the use of a new solid-state photodetector as the readout of a scintillator-based LCD muon system. Such a device could reduce the subsystem cost considerably. Prototype devices have been produced and characterized by aPeak[1], a small company funded by a DoE Small Business Innovative Research award. This proposal will enable a high energy physics group to verify the key performance characteristics and to demonstrate the suitability of the device for use with the LCD muon system.

Background

Scintillating fiber, or Wavelength Shifting (WLS) fiber readout of scintillator strips, is a candidate for Linear Collider Detector systems in central or intermediate tracking or large area muon systems. The standard photodetector for this type of fiber readout is the photomultiplier tube (pmt). The advent of multi-anode pmts has brought the per channel cost of these devices down, 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. They are also very sensitive to magnetic field effects, often leading to large optical fiber cable plants and / or shielding. A fast, cost effective replacement for the pmt would be a valuable addition to the experiment designer's toolkit.

We have been working together with aPeak, a small firm in the Boston area, to develop Geiger-mode Avalanche Photodiodes (GPDs) for these applications. GPDs appear to have several interesting features for these types of applications, including 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 (as proposed here to a modest degree, and to a much larger degree by B. Dolgoshein *et al.*[2]). Such a configuration could be self-triggering by incorporating multiplicity logic in the readout.

The cost-savings from a combination of these factors could reduce the system cost considerably. These Geiger-mode devices produce volt-size signal that do not need a preamplifier and the simple active quench circuit could be done on-chip providing a digital output. Initial cost estimates from aPeak for an 8000-fiber readout system for MINOS-style scintillator / WLS fiber detector are approximately $40 per channel, including the GPD pixel, active quenching circuit and a fiber mount system. Costs for

[1] 63 Albert Road, Newton, MA 02466. General Manager: Dr. Stefan Vasile.
[2] "The Advanced Study of Silicon Photomultiplier": http://www.slac.stanford.edu/pubs/icfa/fall01/paper3/paper3a.html

larger detector system should be even lower. The low voltage power supply and cabling should be somewhat lower than for a pmt HV system. The expected insensitivity to magnetic fields should reduce the optical fiber plant considerably, resulting in a robust, compact, and relatively inexpensive readout system.

The design specification for the GPDs developed as part of this proposal will be optimized for use in a MINOS-style WLS fiber readout of a scintillator bar, such as one which might be used in a linear collider detector muon system. The WLS readout requirements are well understood as a result of tests conducted at SLAC and duplicated at CSU.

The ultimate goal of this project is to produce GPDs optimized specifically for a muon system and in sufficient quantities to allow us to evaluate system performance, reliability and uniformity. We will also be able to address packaging requirements for this specific application. The primary characteristics of interest are detector gain, detection efficiency for minimum ionizing particles transiting the scintillator bar, recovery time, dark count rate and consequent dead time of the detector, performance as a function of temperature, and the long term reliability and stability of the devices. Additionally, the timing performance of the detectors will be investigated to understand the potential track position resolution along the scintillator bar by reading out the fibers at both ends. Timing information might also allow for ungated operation of multi-pixel hits from a single fiber.

Status of Research into GPD Performance

GPD Device Characterization at aPeak

In 2003 we enjoyed significant progress in the evaluation and testing of GPD pixels since aPeak was able to produce a few 150-micron diameter GPD pixels, the largest available to date. Unfortunately these pixels were produced on a wafer commissioned by a customer and could not be shipped to CSU for testing, indeed they were only available to aPeak for a short period.

aPeak performed a standard battery of characterization measurements on these pixels. In particular, the GPDs were demonstrated to have reasonable detection efficiency as measured by a pulsed LED (see below). The active quenching circuitry was demonstrated to provide a ~1 μs recovery time for a pixel (as compared to 10 μs for a passively quenched pixel), and the dark count rate, while still high at ~300 kHz at room temperature, was manageable for our application. In an LCD application one would reduce this with modest (non-cryogenic) cooling. Since the signals have a fast rise time (~5 ns), careful timing allows a low accidental rate with a scintillator hodoscope.

The detection efficiency measurements performed by aPeak use a 550 nm (green) LED to produce 150 ns wide pulses at a rate of 10 kHz; this provides an average of about 10 photons per pulse onto the 150-micron diameter GPD. The GPD output rate is measured while the device is illuminated in this manner. A Dark (Count) Rate is determined in a dark box with no light source. The detection efficiency is then defined as *DE = (Illuminated Rate - Dark Rate)/10 kHz*.

Since the output amplitude of this single photoelectron-sensitive Geiger device is independent of the number of photons detected, the detection efficiency is related to the probability for the average number of detected photons, n_d, to fluctuate to zero, *i.e.* $DE = (1-exp(-n_d))$. The number of detected photons is related to the number of incident photons by, $n_d = QE * A * N_\gamma$ where N_γ is the number photons incident on the photodetector and *QE*A* is an effective single photon detection efficiency related to the surface quantum efficiency at that wavelength, and other efficiency or acceptance effects. LED measurements of the 150 micron GPD at 20°C found *DE* ~ 0.50 for $<N_\gamma>$ ~ 10, which implies *QE*A* ~ 0.07. Other measurements that show the detection efficiency increases and dark count rate decreases with modest decrease in temperature (measurements made a aPeak down to about -30°C). The effective efficiency is expected to improve with better optical coupling.

First Demonstration of WLS Readout with an aPeak GPD

The aPeak device characterization results, shown by Wilson at the January 2003 ALCPG meeting, were encouraging enough to warrant an attempt to measure cosmic ray efficiency with the WLS fiber readout. We summarize here only the cosmic ray results performed by D. Warner and S. Vasile at aPeak using the CSU apparatus. Most of these results were presented at the July 2003 ALCPG meeting.

A limitation of performing the measurements at aPeak was the lack of standard HEP DAQ equipment. However, using digital scope traces from a reference pmt calibrated previously at CSU, we were able to estimate the average number of photons/event at one end of the spliced Y11 fiber used for these measurements. For a 1 mm diameter Y11 core coupled to 0.15 mm GPDs, we find ~4 photons/event incident on the pixel, consistent (within 20%) with the CSU calibration. Using the LED measurement for *QE*A* of 0.069 for the 150 micron GPD at 20°C, we predict a detection efficiency, *DE ~ (1-exp(0.069*4)* ~ 0.24. This neglects additional losses, such as Fresnel reflection at the Y11-GPD interface.

Data were taken over a period of the three days that the devices were available to us. Triple coincidence of the two hodoscope scintillators and the GPD provided the uncorrected signal rate. The accidental coincidence rate was determined by misaligning the hodoscope and scintillator bar. With the efficiency was determined from the ratio of the corrected signal rate and the hodoscope rate. The optimal configuration achieved on the final day, we find a single pixel detection efficiency of 0.21±0.05 (statistical error only), which is consistent with the results from the pulsed LED measurements.

Current research funded by aPeak's SBIR Phase-I Award

In April 2003, aPeak received notice of an award from DOE under the SBIR (Small Business Innovative Research) program for research into GPD performance with applications to scintillating fiber/WLS fiber readout. Warner and Wilson assisted aPeak in developing the proposal for this project, and will be involved in the layout specification and testing of the GPDs produced under this award. Wilson is participating as a consultant; Warner will perform cosmic rays measurements in the CSU-HEP lab under a sub-contract from aPeak.

The SBIR R&D plan envisions two GPD fabrication runs, producing hexagonal 7-pixel arrays from 150 microns diameter circular pixels, Figure 1. The 7-pixel array configuration was chosen because it maintains as much space between pixels as can be achieved while providing a detection probability of near 100% for minimum-ionizing cosmic rays transiting the scintillator bar.

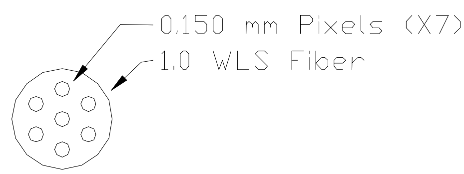


Figure 1 Seven-GPD pixel layout to match a 1.0 mm diameter WLS fiber footprint.

After LED-source characterization at aPeak, the pixel arrays will be sent to CSU for the following additional measurements:

- Detection efficiency for detection of cosmic rays for a 1-mm fiber readout by a 7-pixel array.
- Timing characteristics of GPDs, and techniques for minimizing the impact of dark counts using coincidence techniques.
- Light concentration techniques for focusing fiber output onto pixels.

A critical feature of our involvement with this project is that upon completion of the tests to be performed as part of the SBIR award, CSU will retain four of the pixel arrays from the better of the two fabrication runs. These pixel arrays form the no-cost basis of the first year of this R&D proposal.

PROPOSAL FOR LC DETECTOR RESEARCH

The results from our initial studies of the devices at aPeak are encouraging and we expect to greatly increase our experience with the devices during the SBIR-funded research program. However, thus far no HEP group has had unfettered access to these devices to investigate their use in a specific application. The most important tests of the GPDs required for the muon system can be made with the devices we will keep from the aPeak program plus modest additions to apparatus that already exists at CSU. Without direct HEP funding for technical support, we will not be able to fully validate these promising devices.

The full investigation can be divided into three main phases: (1) Verification of basic GPD properties and readout of small number of channels; (2) Demonstration of larger-scale HEP detector prototype readout (including the possibility of self-triggered operation and possible photon signal amplitude measurement); and (3) Development of the packaging, interface, and physical plant for use in a realistic detector. At each stage a cost comparison with competing technologies will be performed.

Phase I-Year 1 : Device Characterization and Multi-pixel Fiber Readout Demonstration

During the first year of our R&D program, we plan to take advantage of the GPDs we will receive upon completion of the aPeak Phase I SBIR project. As part of the SBIR program, aPeak will continue its investigations of the device properties of GPD pixels, particularly the quantum efficiency and dark count rate as a function of device temperature and bias voltage, the signal time characteristics (jitter and risetime) as a function of bias voltage, recovery time with active quenching circuits, cross talk due to optical and electrical effects, and long term stability and reliability.

While these vendor measurements are essential, it is important that they be duplicated and confirmed by potential users. In particular, we are interested to evaluate the following performance parameters:

Device uniformity: Earlier GPDs, produced by another manufacturer (RMD, Inc., Watertown, MA) showed very significant variation in dark count rate and detection efficiency from pixel to pixel; even for pixels on the same die. The manufacturing techniques used to produce the aPeak pixels are based on robust and well-understood CMOS technology, and aPeak expects to improve the process further, however it will be important to confirm this improvement. CSU will retain 28 individual pixels for tests after the SBIR program, and thus can perform an independent evaluation.

Environmental testing: The dark count rate and detection efficiency of GPDs vary strongly with temperature. Measurements of this effect at aPeak have been conducted by cooling the device to low temperatures (-40°C) and monitoring the variables as the device warms to room temperature. We propose to build an environmental chamber capable of maintaining a fixed temperature between -20°C and 20°C for long periods. This will validate that the transient measurements are representative of long-term performance.

Cross talk: Understanding cross talk between adjacent pixels is critical for optimizing the layout of pixel arrays. Cross talk from dark count signals in one pixel may trigger neighboring pixels so minimizing cross talk reduces dark count rate from the array. However, minimizing cross talk may involve larger separation between pixels, reducing the packing fraction of pixels under a fiber. We will investigate cross talk of dark count signals between pixels in an array by measuring the change in count rate as power to masked adjacent pixels is turned on and off.

Long Term Stability: Linear Collider applications will require long-term stability and high reliability from photodetectors. New devices, such as GPDs, with no “track record” will require extensive reliability testing to confirm that they will function reliably. Typical aging techniques, such as operation at an elevated temperature, have direct real-time effects on GPD operation (dark count rate, detection efficiency) that limit their validity, so we will conduct multi-month tests at known illumination levels with GPDs to look for changes in detection efficiency, noise rate, or timing characteristics. This will be done at various temperatures and illumination levels.

Magnetic field sensitivity: It is expected that the device will be quite insensitive to magnetic fields (certainly more so than pmts), however the extent to which this is true has yet to be demonstrated experimentally. This measurement is beyond the scope of this proposal but the authors anticipate that it will be pursued independently.

In order to facilitate testing of GPDs by CSU at the aPeak facility and to allow us to test GPDs in conjunction with muon system candidates at FNAL or other locations, we plan to develop a dedicated PC-based DAQ system, containing 64 channels of NIM/TTL gated hit register channels, 4 ADC channels, and 2 TDC channels. This will allow us to read out up to 64 GPD arrays in gated operation, with rudimentary timing and pulse height information helpful in understanding GPD performance.

Phase II-Year 2 : Prototype Detector Readout

Upon completion of Phase I, we will have a good understanding of the behavior of the devices and their performance in the readout of a small number of channels in a simple cosmic ray test. At that time others in the LCD Muon Group will have investigated the capability and costs of multi-anode pmt systems. At this point we will evaluate whether it would be appropriate to produce a custom fabrication run for GPD arrays that could be used in conjunction with pmts on a prototype muon system stack. This might entail:

Custom fabrication run: A custom fabrication run of at least 50 pixel arrays would be manufactured to match the LCD muon stack configuration. This larger sample (>350 pixels) would be a test of the phase I predictions for production efficiency and device uniformity.

Detector testing: The GPDs would be mounted to prototype muon system detectors to allow direct comparison with other readout options. This would also be an opportunity to investigate the possibility of using multi-pixel hits to allow ungated operation and extract rudimentary pulse-height information from the pixel array.

At this stage, we will be able to provide a more detailed system cost for comparison with a pmt-based readout.

Phase III-Year 3 : Packaging and Interfacing of GPD arrays

Phase three would move the design from prototype status towards manufacturability, both in terms of the production of the GPDs and the physical plant required to operate them. This would involve:

- Design of optical interfaces (possibly light concentrators) to connect WLS or scintillating fibers to GPD pixel arrays
- Development of cooling systems (such as piezoelectric coolers) to reduce the temperature and provide the required temperature stability for reliable operation
- Optimization of pixel array layouts to minimize cost and maximize performance
- Investigation of on-chip active quenching and signal processing to further reduce costs
- Design of a system to fit within the constraints of a straw-man muon tracking system developed by the muon tracker task.

At the completion of this phase, we would expect to be ready to produce significant numbers of GPD pixel arrays to read out a large-scale muon system prototype.

Institutions and personnel

David W. Warner (engineer), Robert J. Wilson (professor)
Colorado State University, Department of Physics

Contact person

Robert J. Wilson
wilson@lamar.colostate.edu
(970) 491-5033

BUDGETS

First Year (k$):

EDIA	29.4	- 2.5 months eng. (Warner) + 1.5 month technician
Travel	3.0	- aPeak, FNAL (Warner)
M&S	10.5	- Environmental chamber, LED Flasher, WLS Fiber, DAQ
		- Hardware (64 channel PC-mount hit register, ADC & TDC)
Indirect costs @45%	19.3	
TOTAL:	62.2	

Second Year Estimated (k$):

EDIA	20.4	- 2 months eng. (Warner) + 1 month technician
Travel	3.0	- aPeak, FNAL (Warner)
M&S	5.0	- Mounting hardware
Equipment	32.5	- Custom fabrication run for pixel array system.
Indirect costs @45%	12.8	
TOTAL	73.7	

Third Year Estimated (k$):

EDIA	29.4	- 2.5 months eng. (Warner) + 1.5 month technician
Travel	3.0	- aPeak, FNAL (Warner)
M&S	2.0	- Misc. hardware
Equipment	30.0	- Custom pixel layout, active quenching circuits, cooling, etc.
Indirect costs @45%	15.5	
TOTAL	79.9	

Appendix A: Relevant experience

For several years, the proposers have been advisers to two small businesses, Radiation Monitoring Devices Inc. and aPeak, assisting them with the development of HEP applications for High Gain Avalanche Photodiode Arrays. They have helped them to write successful SBIR proposals (Phase I and Phase II), have contributed to their DoE status reports and have co-authored IEEE papers. Wilson has given several talks on the use of UV sensitive photodiodes for use in imaging Cerenkov applications.

They have extensive experience with photomultiplier tube associated with the BaBar DIRC system. They designed, built and operated the pmt test system for the 500-pmt DIRC prototype (they also designed and built 13,000 photomultiplier tube bases and the high voltage distribution system). At various levels they have also been involved in the design, fabrication or operation of multiwire proportional chambers, drift chambers, single-electron sensitive TPC for imaging Cerenkov readout, resistive plate chambers, lead-scintillator calorimeter, straw tracker *etc.*