7. Muon and Particle ID Systems

Introduction to Muon and Particle ID Systems 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.

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(renewal)

Muon System

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Institution(s)
Indiana
Northern Illinois
Notre Dame
Wayne State
Fermilab
Colorado State
INFN Frascati (Italy)
INFN Udine (Italy)

FY07: 197,000

STATUS REPORT

Scintillator Based Muon System R&D

Personnel and Institution(s) requesting funding

Robert Abrams and Rick Van Kooten, *Indiana University, Bloomington, Indiana*.

Gerald Blazey, Alexandre Dychkant, David Hedin, Victor Rykalin and Vishnu Zutshi, *Northern Illinois University, DeKalb, Illinois.*

Mike McKenna and Mitchell Wayne, *University of Notre Dame, Notre Dame, Indiana*.

Alfredo Gutierrez and Paul Karchin, *Wayne State University, Detroit, Michigan*.

Collaborators

Alan Bross, Brajesh Choudhary, H. Eugene Fisk, Kurt Krempetz, Caroline Milstene, Adam Para, and Oleg Prokofiev, *Fermilab, Batavia, Illinois*.

Robert Wilson and David Warner, *Colorado State University, Fort Collins, Colorado*.

Marcello Piccolo, *INFN, Laboratori Nazionali di Frascati, Frascati, Italy.*

Giovanni Pauletta, Diego Cauz and Lorenzo Santi, *Universita di Udine and INFN Trieste – GC Udine, Italy.*

Project Leaders

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Project Overview

The importance of an ILC muon system is widely recognized in the ILC physics community. A stable, highly efficient detector with excellent hadron rejection is a key requirement to accomplish the ILC physics program. Designing a cost-efficient system that meets this challenge requires significant R&D.

A strong candidate detector technology that has emerged is based on a MINOS inspired scintillator strip design. The scintillator strips would be inserted into slots in the magnet yoke. The current baseline readout utilizes wavelength shifting optical fibers (WLS) fused to clear fibers connected to a Hamamatsu multi-anode photomultiplier tube (MAPMT). However, an important technology has emerged that has the potential to drastically reduce the cost: silicon photomultipliers (SiPM) connected directly to the WLS fibers, or, possibly, directly connected to the scintillator. Our R&D goal is to accelerate the development of scintillator/SiPM detectors that will be applicable to ILC calorimetry as well as muon detection.

A current limitation of using SiPMs is the difficulty in procuring these devices. To encourage industrial development and application in high-energy physics, we submitted a separate supplemental proposal in which Fermilab will act as a central agent in contacting suppliers, procuring devices, testing and packaging them. This has the advantage that industrial suppliers will see that there is a large potential market, and a major buyer with well-established expertise with large scale systems of silicon micro-strip and pixel detectors. The university collaborators will oversee the portion of procurement funds for SiPMs under the supplemental proposal and it is expected that Fermilab can match those funds from a separate source.

With support from this "base" proposal, the SiPMs will be installed in calorimeter and muon prototype detectors and tested with hadron and muon beams at the Fermilab Meson Test Beam Facility (MTBF). The calorimeter prototypes designed and built by NIU and Fermilab will be the first fully integrated scintillator/SIPM devices. The scintillator and SiPM will be mounted together on large circuit boards which also carry the signal traces which converge upon a signal connector. For the muon prototype, the SiPMs will be mounted on small circuit boards at the ends of each scintillator. To study the time structure of the light signals, we will employ MAPMT readout for some strips. In addition, the MAPMT readout will serve as a baseline for comparison with SiPM readout.

The digitization and readout electronics will be common for SiPM and MAPMT front-ends. An existing system designed for the Minerva experiment at Fermilab will be implemented for this project and will provide charge and timing measurement of the front-end signals. University collaborators will work with Fermilab to build and test these electronics. Equipment costs for the electronics will come from outside this proposal, through Fermilab.

In addition to Fermilab, three other institutions will participate in this work, but do not request funding in this proposal. Colorado State will provide samples of GPDs (Geiger-mode avalanche Photodiodes, a type of SiPM) developed by aPeak Inc. INFN Udine will collaborate in detector development and SiPM characterization and procurement, particularly insofar as the SiPMs produced by ITC-IRST, Trento, with whom they already have an established rapport, are concerned. Both INFN Udine and INFN Frascati will collaborate on beam tests.

Status Report

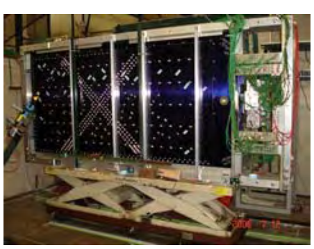
Summary of ILC Muon Prototype Testing

In January-February 2006, a set of four 64-element, 1.25m X 2.5m prototype planes was assembled in a frame, mounted on a hydraulic lift table, and installed in the Fermilab Meson Test Beam Facility. The scintillators were at +/- 45° angles to the edges of the planes (two at +45° and two at -45°). Two planes had single readouts from one end of the scintillators (S planes) and two had dual readouts (D planes), from both ends of the scintillators with 2 MAPMTs (a and b). After a brief run in February, results were presented at LCWS06 at Bangalore.

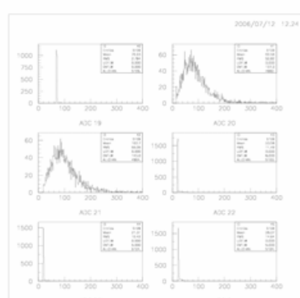
Between February and June 2006, a number of improvements were made to the experimental setup.

- A remote control system was installed to operate the vertical motion of counters on the table without entering the beam enclosure.
- A motor driven transport was installed to provide horizontal motion of the table, with remote controls.
- A laser beam alignment system was installed to project the beam position on the set of counters
- A video monitoring system was added to view the position of the counter and the laser alignment lines.
- The number of channels that were instrumented and cabled was doubled from 24 to 48. This also reduced the number of accesses and led to more efficient use of beam time.

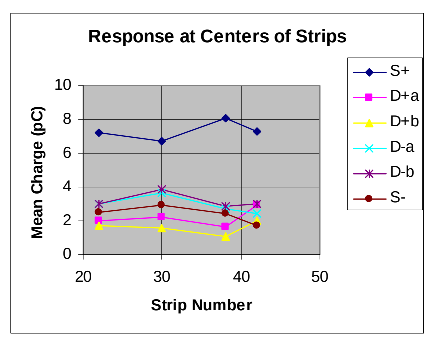
In the late summer of 2006, there was another run in MTBF. The goals of the run were to measure the performance of the central strips that run the full 1.77 m length of the strips, and to compare the dual readout planes with the single readout planes. On that occasion, a strip equipped with SiPMs from ITC was also tested. Some preliminary results were presented at the Vancouver Linear Collider Workshop in July, and analysis of the data is currently underway.



(a)



(b)



(c)

Figure 1(a) shows the detector in place at MTBF. Figure 1(b) shows a typical pulse height distribution for the two ends of a dual readout strip with the beam near the center. Figure 1(c) shows the response at the centers of a number of strips, in units of mean charge.

Silicon Photomultipliers

We propose to evaluate Silicon Photomultipliers (SiPMs) for photodetection. SiPMs are room temperature photo-diodes operating in the limited Geiger-mode with performances very similar to conventional photo-multiplier tubes i.e. they have high gain (~ 10^6) but relatively modest detection efficiency (quantum x geometric efficiency ~ 15-20%). Not only is the signal obtained for minimum ionizing particles with these devices large (~ 10 photo-electrons for our 1 cm thick extruded scintillator strips), their small size (1mm x 1mm) and low bias voltage (30-80 V) implies that they can be mounted in or very close to the scintillator (see Figs. 2 and 3). Consequently little light is lost since it does not travel large distances in the fiber to the photodetector, the need for interfacing to a clear fiber (connectors, splicing etc.) is obliterated and the quantity of fiber required is significantly reduced. Even more importantly, the generation of electrical signals, inside the detector, at or close to the scintillator surface eliminates the problems associated with handling and routing of a large number of fragile fibers. Our investigations into the characteristics of these photodetectors confirms their suitability for calorimetric and muon detection applications. This conclusion was reached based on our studies into their operating bias voltage, dark rate, linearity of response, temperature dependence, stability, radiation hardness and immunity to magnetic fields. The results of our studies are given in [1] [2].

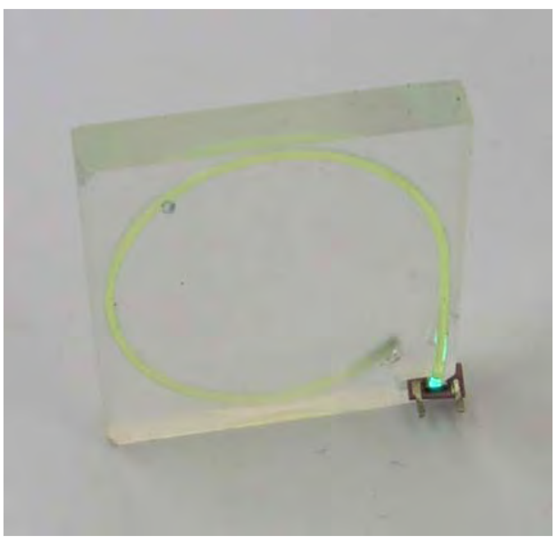


Fig. 2: Example of a SiPM mounted in the scintillator as in an HCAL tile.

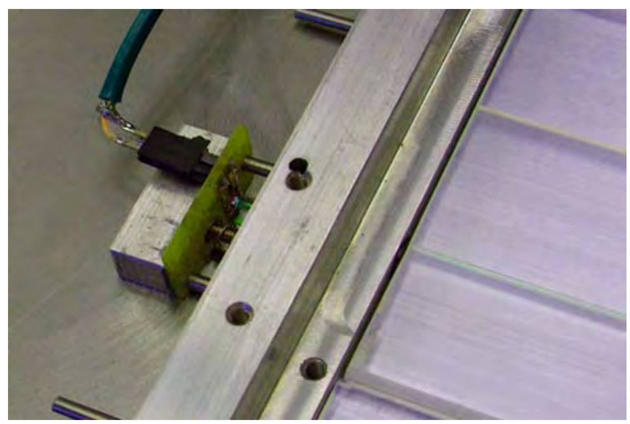


Fig. 3: Example of a SiPM mounted close to the scintillator as for the muon detector.

References:

1) "Investigation of a solid-state photodetector", (NIM A545:727-737, 2005)

2) "Effects of the strong magnetic field on LED, extruded scintillator and MRS photodiode" (NIM A553:438-447, 2005)

Tail-Catcher Muon Tracker

As part of the CALICE program, a silicon-tungsten electromagnetic calorimeter and a steel-scintillator hadron shower imager (see Fig. 4) took beam in the H6B area at CERN in August and October of this year. The hadron shower imager physically consists of two devices; a hadron calorimeter (HCAL) and the tail-catcher/muon tracker (TCMT). Both devices use SiPMs to read out scintillator with embedded WLS fiber.

NIU had primary responsibility for the TCMT which represents the first scintillator-steel muon detector prototype using SiPMs as the photo-detectors. The TCMT prototype has a fine and coarse section distinguished by the thickness of the absorber plates. The fine section sitting directly behind the hadron calorimeter and having the same longitudinal segmentation as the HCAL will provide a detailed measurement of the tail end of the hadron showers which is crucial to the validation of hadronic shower models since the biggest deviation between models occurs in the tails. The following course section serves as a prototype muon system for any design of the ILC detector and will facilitate studies of muon tracking and identification within the PFA reconstruction framework. Additionally, the TCMT will provide valuable insight into hadronic leakage and punch-through from thin calorimeters and the impact of the coil on correction for this leakage.

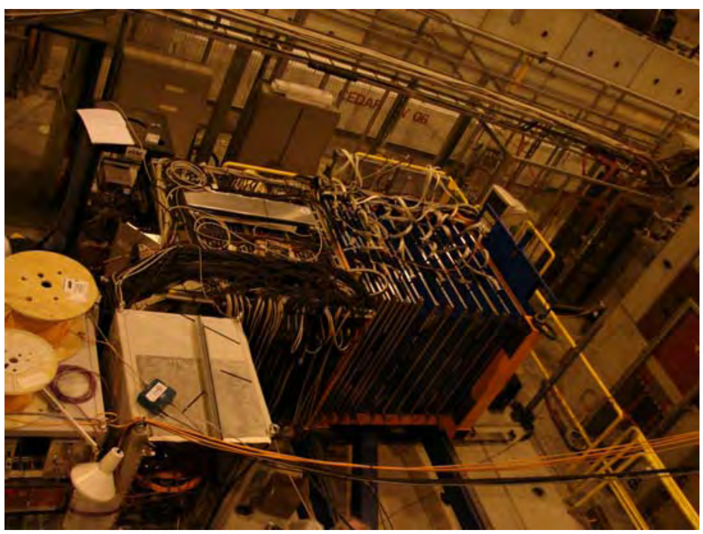


Figure 4: CALICE apparatus in CERN H6B test beam.

The active layers of the TCMT consist of 1m long, 5 cm wide and 5 mm thick extruded scintillator strips. A 1.2 mm outer diameter Kuraray WLS fiber is inserted into the co-extruded holes that run along the length of the strips. The strips and their associated SiPMs in each layer are enclosed in a light tight sheath or cassette. (See Fig. 3.) The top and bottom skins of the cassette are formed by 1 mm thick steel with Al bars providing the skeletal rigidity. The cassettes are inserted, alternately in the X and Y orientation, in a steel absorber stack which has a fine and coarse section. The upstream fine section consists of eight 2 cm thick steel plates while the coarse section is comprised of 10 cm thick steel absorber for a total of approximately six interaction lengths. Both the HCAL and TCMT use common electronics and DAQ boards developed by the CALICE collaboration as a whole.

Over a period of twenty one days in August and October approximately 25M electron, positron, pion and proton events in the 6-80 GeV/c momentum range were collected. Also written to disk were approximately 40M muons of undetermined momenta. These muon events were collected during parasitic running periods, with large area trigger counters (1m x 1m). For calibration and monitoring purposes approximately 14M pedestal and LED events were taken at regular intervals. Analysis of this data has begun and looks promising. Figure 5 shows the uniformity of MIP response derived from muon events for an entire 20-channel TCMT plane.

In preparation for the CERN beam tests, fully instrumented TCMT cassettes of active planes were tested in electron beams at DESY and subsequently in hadron beams at Fermilab. These tests were instrumental in evaluating the SiPMs, the full electronics and data acquisition chain, and in verifying overall performance of the scintillator and SiPMs. This capability remains intact at Fermilab.

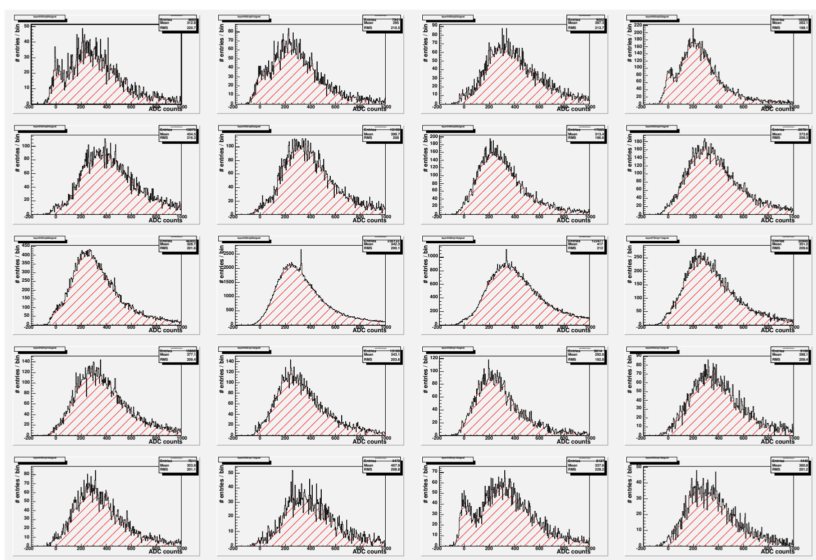


Figure 5: Muon MIP Response in a full plane of the TCMT.

FY2007 Project Activities and Deliverables

1) SiPM Characterization for Muon Detection

We will collaborate with Fermilab on their purchase of SiPM’s from existing commercial vendors in quantities that will permit characterization of the devices and construction of single plane full prototype muon modules. We will also collaborate with Fermilab to characterize the SiPM’s at SiDet. Studies will involve the determination of the working point, dark rate, and linearity of response, temperature dependence, stability, radiation damage and immunity to magnetic fields. Furthermore, we will design a robust packaging for these sensors which is optimized for their installation in the integrated active layer. This work will also be done at Fermilab's SiDet facility.

2) Scintillator Detector Construction

Based on tests of scintillator planes at both NIU and Fermilab we will use extruded scintillator with a cross-section that is approximately 1 cm X 4 cm with an extruded longitudinal hole that is slightly larger than the 1.2 mm diameter of existing wave-length shifting (WLS) fiber. We will employ a new die in the production of the scintillating strips here at Fermilab using the NIU/NICADD extrusion machine in Lab 5. The outside of the strips will be covered with TiO_2 that is co-extruded with the scintillator during the extrusion process. The length of the strips for the 1.25 m X 2.5 m planes is a maximum of ~1.8 m. Each plane is composed of 64 strips. Reimbursement for the cost of a new die and the scintillator (~$10K) is not part of the request for funding in this supplemental proposal.

The 1.2 mm diameter WLS fiber that is inserted in the long hole in the extruded scintillator will be brought into contact with the light sensitive area of a SiPM or MPPC based on techniques previously developed at NIU in collaboration with our colleagues at Notre Dame and Indiana Universities and Fermilab. The assembly of additional 1.25m X 2.5m muon planes will most likely take place at UND.

We will equip a fraction of the strips with a thermally fused WLS to clear fiber that can be readout using our previously developed MAPMT technology. This will allow a direct comparison of the SiPM and MAPMT technologies.

3) Front-end Electronics and Readout

For a minimum ionizing particle the typical integrated charge from either a SiPM or a MAPMT is ~ 2pC. Fermilab has developed front-end boards with readout that digitize timing and pulse-height signals, provide high-voltage for the SiPM's, and communicate with VME-resident readout controller modules over a Low-Voltage Differential Signal (LVDS) token-ring. Pulse-heights and latched times will be read from all channels at the end of each spill. The front-end board, which is also used for the Minerva experiment, is designed around the D0 TRiP ASIC which is a redesign of the readout ASIC for the D0 fiber tracker and pre-shower detectors.

Each front-end board services 64 SiPM's, which requires 4 TRiP chips per board. The TRiP chips are controlled by a commercial FPGA (Field-Programmable Gate Array) using custom firmware. A prototype of this firmware has already been developed and successfully operated. In addition to digitization of charge and timing information, the front-end boards can also supply high-voltage to the SiPM's and communicate with the downstream readout system over the LVDS link.

The Minerva boards are based on the D0 TRiP ASIC that is in turn based on the SVX4 chip design. Each TRiP chip supports 32 channels for digitization, half of which are available for discrimination and timing. Each channel has a pre-amplifier whose gain has two settings which differ by a factor of four. A second variable gain amplifier stage is also available; its gain is set with switches. In this way input signals whose maxima range from 5 to 50 pC are accommodated. The analog output is received by an analog pipeline, 48 cells deep, that is identical to the one used on the SVX4 chip. To gain dynamic range, the input to the electronics can be modified with a passive divider to divide charge from a single SiPM between two TRiP channels with a ratio factor of 10. Each TRiP channel is digitized by a commercial 12-bit ADC.

The design, based on shower energy loss, requires no saturation below 500 photoelectrons (PE) and an RMS noise well below 1 PE. Matching this to the 5 pC charge limit, the highest gain could be set at 100~fC/PE. The integration time for the ADC in this example will be 10-12μs, which is much less than the hold time for the charge in the capacitor of 100 μs. Prototype boards have been tested explicitly with a 10 μs gate, and the measured pedestal RMS was <2 fC. This will put a single photoelectron a factor of 10 or more above the pedestal RMS, well within our requirements. This same electronics will work for digitization of MAPMT signals where the maximum gain for the lowest gain anode will be 50~fC/PE, which is safely within the desired parameters above.

Each board includes its own high-frequency phase-locked oscillator, which provides a local clock signal for the FPGA logic. Global synchronization is provided using an external counter-reset reference signal distributed over the LVDS interface from the VME readout boards once every second, which can be synchronized to the beam structure.

A resonant mode (low) high-voltage generator, mounted on a daughter card, will provide power to each board's SiPM's. The daughter-card design will allow a malfunctioning high-voltage supply to be easily replaced without changing the main readout board. A controller based on the Fermilab RMCC chip will allow the SiPM voltage to be monitored, adjusted or disabled under computer control, using the LVDS interface to the board.

4) Beam Tests

After SiPM detectors are qualified at SiDet and installed in scintillator planes we will need to test them with charged particle beams at the Fermilab MTest facility as we have done with previous prototype detectors. We will need to qualify new electronics as well as new detectors. We will be stepping up from ~100 channels to ~1000 channels or more and will need to develop and qualify software associated with the new electronics as distinct from data acquisition software, which will also be new.

We expect to expose our detectors to both hadrons and muons. We need to establish the signal-to-noise ratios as a function of strip position and length and to verify expectations for performance.

Developing the software for carrying out beam tests will require personnel with software expertise as will the analysis of test beam data.

Project Activities and Deliverables Beyond FY2007

We plan to build and test full scale muon detector planes and instrument one barrel and one end cap sector in FY2008 and FY2009. The purpose is to establish a reliable cost and performance baseline for a technology choice decision for the muon system.

Budgets

Total Project Budget, in then-year k$

Item	**FY2007**
Other Professional	83
Graduate Student	17
Undergraduate Student	0
Total Salaries and Wages	**101**
Fringe Benefits	23
Graduate Student Fee Remission	4
Total Salaries, Wages and Benefits	**127**
Equipment	4
Total Travel	15
Materials and Supplies	11
Other Direct Costs	0
Total Direct Costs	**157**
Indirect Costs (26% of MTDC)	39
Total Direct and Indirect Costs	**197**

Budget, in then-year k$
Institution: Indiana University

Item	FY2007
Other Professional	22
Graduate Student	
Undergraduate Student	
Total Salaries and Wages	**22**
Fringe Benefits	7
Graduate Student Fee Remission	
Total Salaries, Wages and Benefits	**29**
Equipment	
Total Travel	4
Materials and Supplies	
Other Direct Costs	
Total Direct Costs	**33**
Indirect Costs (26% of MTDC)	9
Total Direct and Indirect Costs	**42**

Budget justification: Indiana University

Funds are requested for 6 months salary each year for a research physicist (replacement for Robert Abrams). He will lead the test beam effort at Fermilab. Travel support is requested for the research scientist and P.I. Van Kooten for trips to Fermilab and an ILC conference.

Budget, in then-year k$
Institution: Northern Illinois University

Item	**FY2007**
Other Professional	22
Graduate Student	
Undergraduate Student	
Total Salaries and Wages	**22**
Fringe Benefits (20%)	4
Graduate Student Fee Remission	
Total Salaries, Wages and Benefits	**26**
Equipment	
Total Travel	2
Materials and Supplies	3
Other Direct Costs	
Total Direct Costs	**31**
Indirect Costs (26% of MTDC)	8
Total Direct and Indirect Costs	**40**

Budget justification: Northern Illinois University

The major item is four months support for a professional (either Dychkant or Rykalin) who will take major responsibility for detector operation with the test beam. Both have extensive experience with detector construction and operation including the recent TCMT beam tests. (These funds may be used for a graduate student should one be recruited in a timely manner.)

Some funding will be required for test beam equipment and a small mount for travel to Fermilab and ILC meetings.

Budget, in then-year k$
Institution: University of Notre Dame

Item	FY2007
Other Professional	30
Graduate Student	5
Undergraduate Student	
Total Salaries and Wages	**35**
Fringe Benefits (20% of Other Prof.)	6
Graduate Student Fee Remission	
Total Salaries, Wages and Benefits	**41**
Equipment	4
Total Travel	2
Materials and Supplies	
Other Direct Costs	
Total Direct Costs	**47**
Indirect Costs (26% of MTDC)	11
Total Direct and Indirect Costs	**58**

Budget justification: University of Notre Dame

Support is requested for 50% of the salary of one technician, Mr. Mike McKenna. Mr. McKenna is a skilled technician with more than 25 years of experience working in particle physics. He has worked the majority of his career (more than 20 years) at Fermilab and is now a member of the Notre Dame HEP group. We also request support for 25% of a single graduate student to work summers on detector construction, and later, data analysis. Equipment funds are needed to constuct the various tables, jigs, transports and other apparatus needed for detector assembly. Finally, a small amount of travel funds are budgeted to cover the cost of transportation of materials between Notre Dame and Fermilab.

Budget, in then-year k$
Institution: Wayne State University

Item	FY2007
Other Professional	9
Graduate Student	12
Undergraduate Student	
Total Salaries and Wages	**22**
Fringe Benefits (26.4%)	6
Graduate Student Fee Remission	4
Total Salaries, Wages and Benefits	**31**
Equipment	
Total Travel	7
Materials and Supplies	8
Other Direct Costs	
Total Direct Costs	**46**
Indirect Costs (26% of MTDC)	11
Total Direct and Indirect Costs	**57**

Budget justification: Wayne State University

Salary support is requested for 2 months per year for Research Engineer Alfredo Gutierrez in support of MAPMT and SiPM instrumentation and testing. He has 10 years experience with computers and electronics for high energy physics experiments and has 3 years experience with MAPMT work for this project.

Support is requested for a graduate student for one academic term and during the summer, each year, to perform calibration measurements, take data using the prototype modules at Fermilab and to analyze the data.

Travel support is requested for 2 1-week trips to Fermilab for the student, 4 trips of 2 days each to Fermilab for the P.I. and for travel to a domestic and international conference for the P.I.

Funds are requested to purchase 2 MAPMTs and 2 SiPMs and associated electronics components per year to develop calibration and monitoring procedures for the prototype modules. Minor costs are also included for shipping of materials.

7.5: Continuing Studies of Geiger-Mode Avalanche Photodiodes for Linear Collider Detector Muon System Readout

(renewal)

Muon System

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Institution(s)
Colorado State
aPeak Inc.
Fermilab
Indiana
Northern Illinois
Notre Dame
Wayne State
INFN Frascati (Italy)
INFN Udine (Italy)

FY07: 14,000

Continuing Studies of Geiger-Mode Avalanche Photodiodes for Linear Collider Detector Muon System Readout: *Status Report and 3rd 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. They are currently involved with the evaluation of photosensors for the pi-zero subsystem of the T2K experiment.

Collaborators

- Stefan Vasile; President, aPeak Inc.
- Alan Bross, Brajesh Choudhary, H. Eugene Fisk, Kurt Krempetz, Caroline Milstene, Adam Para, and Oleg Prokofiev, *Fermilab, Batavia, Illinois*.
- Robert Abrams and Rick Van Kooten, *Indiana University, Bloomington, Indiana*.
- Gerald Blazey, Dhiman Chakraborty, Alexandre Dychkant, David Hedin and Vishnu Zutshi, *Northern Illinois University, DeKalb, Illinois.*
- Mike McKenna and Mitchell Wayne, University of Notre Dame, Notre Dame, Indiana.
- Alfredo Gutierrez and Paul Karchin, *Wayne State University, Detroit, Michigan*.
- Marcello Piccolo, *INFN, Laboratori Nazionali di Frascati, Frascati, Italy.*
- Giovanni Pauletta, Diego Cauz and Lorenzo Santi, *Universita di Udine and INFN Trieste – GC Udine, Italy.*

Project Leader

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Project Overview

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 or calorimeter system for a Linear Collider Detector (LCD). We report on several significant positive developments during the past year.
The majority of funds for the investigation thus far have been provided by a sub-contract from aPeak Inc., but for the past two years this work was supplemented by modest awards ($14,000

per year) through 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 tightly coupled to the requirements of Linear Colliders detectors. Indeed, during the past year the strong working relationship that has developed led to an agreement by aPeak to develop a new device more closely matched to current LCD requirements than earlier versions. 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[1]. aPeak is currently the only US developer of these devices.

This proposal is a 3rd-year continuation of our LCD motivated research into Geiger-mode Avalanche Photodiodes applications. The modest level of funding has allowed us to leverage the substantial ($735,000) commercial investment and influence the commercial development of a very promising technology towards potential use the LCD muon system. This past year was particularly successful in that regard. A great deal of critical research on GPD performance has been supported by this SBIR funding, but that source ends in early 2007. We have some LCRD funds to carry over from 2006 (that contract was not received until late in 2006), but it is essential that LCRD funding continue to allow us to continue to interface with the LCRD muon group.

Status Report

Last year we reported on successful performance measurements of the temperature dependence of single pixel GPDs using a control and readout system developed with a combination of LCRD and aPeak SBIR funding. The positive results from those measurements encouraged aPeak to produce a device containing a single chip, just 1 cm on a side, capable of reading out 64 1-mm diameter fibers (Figure 1). We summarize here tests of this device at CSU, including first demonstration of multi-photon counting and the recent development of individual pixels with greater calorimetric bandwidth motivated by the requirements of the LCD muon system.

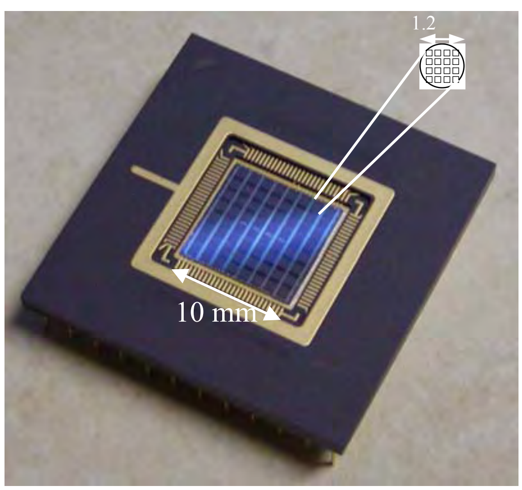

Fig. 1: 64-fiber readout prototype device produced by aPeak Inc.
[Proprietary information under the FOIA act.]

[1] 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 three years of the collaboration.

The design goal for this device was for a high efficiency, high-density, compact, cheap WLS/fiber readout primarily for non-calorimetric use, such as a tracking system. It consists of 64 x 1 mm^2 fiber readout on a single chip where each pixel consists of a cluster of sixteen 160x160 μm^2 GPDs on 240 mm centers. Rather than being simply a binary yes/no response as in previous aPeak designs, the output of this device is proportional to the number of hit GPDs. This provides sufficient amplitude information to allow hit threshold tuning, while maintaining a good geometrical efficiency (0.45 for a 1.0 mm diameter fiber and 0.36 for 1.2 mm fibers).

To investigate the photosensor performance we used a 550-nm LED that could be pulsed at a high rate. We calibrated the output intensity of the LED by measuring the response of a photomultiplier tube (EMI 911B) and comparing this to the same pmt response to cosmic rays passing almost vertically (defined to be 1 "VCR") through a MINOS bar provided by the LCD muon group. The LED voltage and pulse widths were adjusted so the response of the pmt approximated 1 VCR. As indicated in Figure 2, the peak position and width match well, but the high charge tail is not reproduced. The 1 VCR peak corresponds to about 200 photons exiting the WLS fiber in our configuration. Though this scheme does not provide an absolute calibration (for example, the monochromatic LED light does not match the WLS spectrum), it does allow for high rate measurements of the general response of a test pixel over a range of intensities.

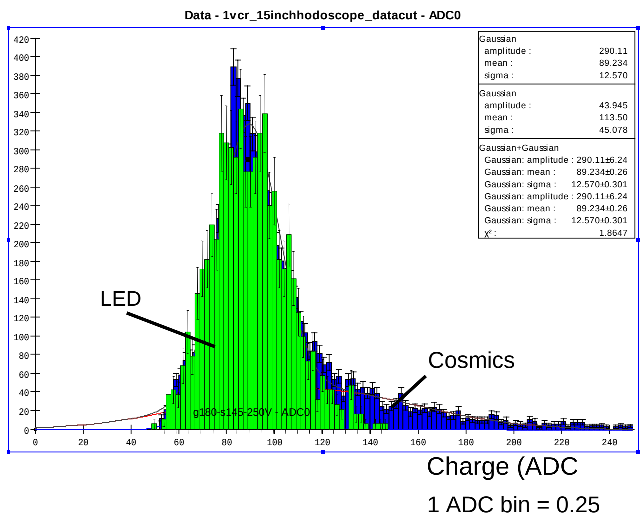

Fig. 2: Matching pmt response to cosmic rays in a MINOS bar to 550 nm LED pulses.

In Figure 3 we show the integrated charge response of a single pixel (10x amplification and 500 ns integration time) as a function of the light intensity from the LED expressed in units of the light output of a single cosmic ray described earlier. The device shows good linearity up to roughly 1.2 VCR (240 incident photons) then rolls over as the 16-GPD pixel saturates. The rollover region is consistent with previous single GPD detection efficiency measurements. Figure 4 shows the detection efficiency of a pixel as a function of the measured charged for a range of incident intensities at room temperature. The data indicate that high detection efficiency is possible at modest light levels. Finally, although single photon resolution was not a design goal for this device (and is not evident at room temperature), we have demonstrated photon counting capability at low temperatures. Figure 5 shows the integrated charge response of a pixel exposed to a light intensity equivalent to one cosmic ray at a temperature of -19°C.

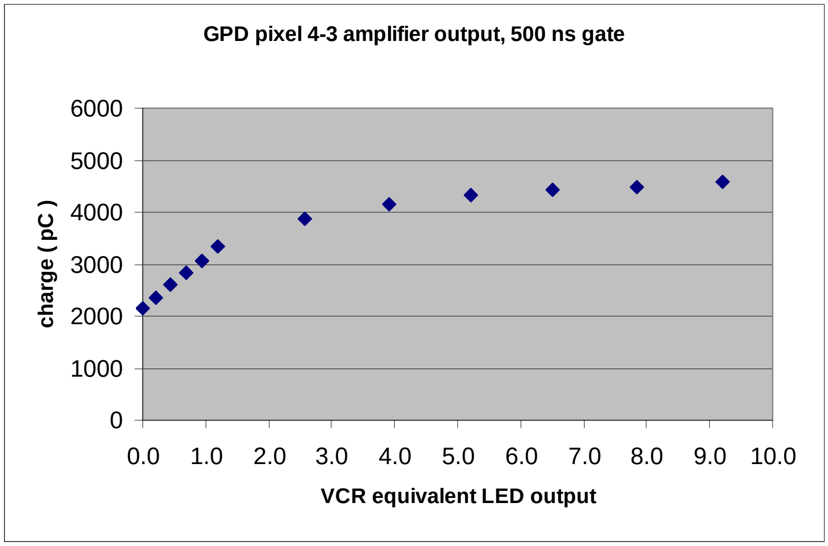

Fig. 3: GPD response (peak of the charge) distribution as a function of LED light intensity equivalent to the light yield from a MINOS bar.

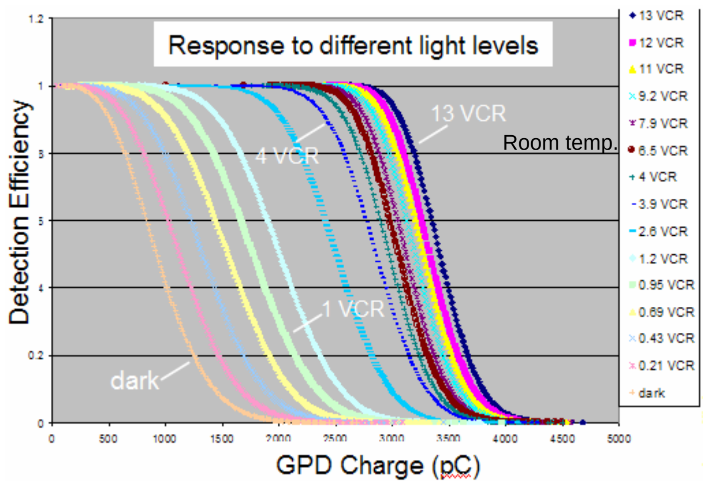

Fig. 4: Detection efficiency of a pixel as a function of the measured charged for a range of incident intensities.

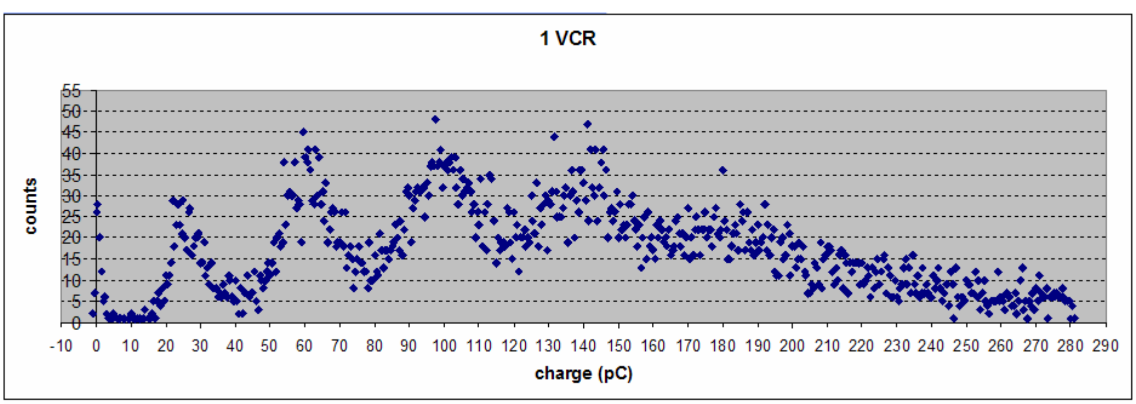

Figure 5: Demonstration single photon resolution for 1 vertical cosmic ray equivalent LED output at -19°C. The peaks correspond to 1, 2, 3, 4, etc. photoelectrons.

We have completed a systematic investigation of the response of the device to intensities ranging from a one photon per pixel to thousands, and over a temperature range of 25°C to -19°C. Preliminary results were presented by Wilson at the 2006 ILC Physics and Detector Workshop (Vancouver, Canada) and a paper has been submitted by Stefan Vasile (aPeak Inc.) to the 2006 IEEE Nuclear Science Symposium. Further analysis and compilation of these data will be included in the final aPeak SBIR report mid-2007 and reported at a future ILC workshop.

Project Activities, Deliverables, and Budgets

The initial motivation for the high-density 64-channel device was as a cost-effective and magnetic field insensitive replacement for the LCD Muon System baseline MAPMT. A target activity of the original aPeak SBIR proposal was to demonstrate the performance of the device in a beam test with the LCD Muon System prototype. Due to funding and synchronization limitations this test did not occur. However, during the past two years it has become apparent that a more effective approach to the muon system readout might be to use individual solid state photosensors on each WLS fiber. The scheme has been adopted by the T2K collaboration for all of the scintillator based subsystems in that experiment – more than 100,000 channels.

In 2006, the CSU group joined the T2K collaboration, and accepted responsibility for the evaluation and selection of the solid state photosensors for the roughly 11,000 channel WLS/scintillator pi-zero reconstruction subsystem. The current candidate sensors are the MRS from Russian supplier CPTA, and the MPPC from Hamamatsu Photonics (HPK). CSU will also design the photosensor optical connector that will be used in several of the subsystems. The activities related to that project combined with our experience with the aPeak GPDs will greatly leverage the contributions to the LCRD effort that would be enabled by a continuation of LCRD funds.

As a result of the desire of the LCD Muon group to have greater dynamics range in the photosensor readout, we have persuaded aPeak to develop a single pixel device with a larger number of GPDs per pixel that will not only provide a higher dynamic range but may also provide photon counting similar to the Russian and Japanese devices. The first version of that device will be delivered to CSU in early 2007 – if this effort is successful it may lead to the first US-based source for these devices. In March 2007, in conjunction with test of a T2K prototype, we have made plans for a beam test with a single MINOS bar on which we will test the aPeak devices along with the MRS and MPPC so we can do a direct comparison (thanks to our T2K connection, we have some of the few MPPCs outside of Japan). Members of the Muon Group are supplying materials and assisting with the preparations for this test. In addition to Wilson and Warner, additional CSU participants in the beam test will include two post-doctoral researchers Dr. P. Bauleo and Dr. Y. Caffari along with lab assistant E. Martin. This activity is funded primarily by our aPeak sub-contract and the 2006 LCRD award.

The information we get from this test will be invaluable to the large scale test proposed by the Muon group in a separate LCRD proposal. With the continuation of the current level of LCRD funding we will be able to contribute to that effort, for example it has been suggested that we could assist with the optical connector design and fabrication since their requirements will be very similar to our T2K design.

2007 Project Activities and Deliverables

In 2007 we will: (1) analyze the data collected with the GPD, MRS and MPPC mounted on a single MINOS bar in a Fermilab test beam (2) present the results at a Linear Collider Detector Workshop or similar forum (2) and assist with the development of the larger scale LCD muon system prototype described by Karchin, Fisk et al. in a separate proposal. We will also continue to work with aPeak Inc. to facilitate the development of a US-based vendor for these promising devices.

Budget Justification

A continuation of the current level of funding (Table 1) would provide funds for approximately 144 hours of EDIA by D. Warner (at the Technical Design Facility rate of $55 per hour) and two 2-day trips (@ $650 each) to the Chicago area or Linear Collider Detector workshops for coordination of this effort. This modest level of support would allow us to sustain a basic presence and linkage between the only current US developer of SiPMs, the first large-scale use of SiPMs in a High Energy Physics experiment and with the LCD R&D program.

Table 1: Budget

Item	Total
Other Professionals (D. Warner)*	$ 7,924
Graduate Students	-
Undergraduate Students	-
Total Salaries & Wages	**7,924**
Fringe Benefits (grad. student only @ 3.6%)	-
Total Salaries, Wages & Fringe Benefits	**7,924**
Equipment	$0
Travel	1,300
Materials & Supplies	300
Other Direct Costs	-
Total Direct Costs	**9,524**
Indirect Costs (46%)	4,476
Total Direct & Indirect Costs	**$14,000**

* 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%.

7.8: RPC and Muon System Studies

(new proposal)

Muon System

Contact person
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(510) 926-2655

Institution(s)
Wisconsin

FY07: 146,550

ILC Detector R&D Proposal

RPC and Muon System Studies

Henry Band and Kevin Flood
University of Wisconsin

Collaborators

KPIX data acquisition chips will be provided by M. Breidenbach, D. Freytag, G. Haller, and R. Herbst of the Stanford Linear Accelerator Center (SLAC).
Small test chambers of the BESIII RPCs have been provided by
Changguo Lu of Princeton University, Y. Wang and J. Khang of IHEP.
Muon identification algorithms and detector simulation studies will use the LCSim software framework developed and maintained by N. Graf et al., SLAC.
No funds are sought for these collaborators.

Project Leader

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510-926-2655

Project Overview

Introduction

All four of the ILC detector concepts propose muon systems outside the central solenoid to provide muon identification. The muon system detectors should be low cost, reliable, and efficient. Several detector technologies have been proposed. Resistive Plate Chambers (RPCs) of various types are the likely lowest cost option. This project proposes to study the parameters and performance of an ILC muon system through detector simulation, to determine a cost-optimized design, and to develop muon identification algorithms within the LCSim simulation framework, thus forming a solid foundation for an ILC detector conceptual design in FY08. It also proposes to study the RPC detector option through studies of RPC aging with existing and proposed RPC designs, and to develop and test RPC prototypes for the SiD detector concept. These RPC studies benefit not only the muon system but are applicable to possible uses of RPCs in the hadronic calorimeter.

RPCs, however, may have a nontrivial technical risk as demonstrated by problems experienced by the RPCs installed at the B Factory detectors. Our study of the BaBar RPCs sparked a large detector study effort culminating in a new generation of RPCs for BaBar, ATLAS and CMS. The 2^{nd} generation BaBar RPCs built under our supervision have been much more reliable, particularly when operated in streamer mode at low rates, as expected for an ILC muon system. Test RPCs for ATLAS and CMS, operating in avalanche mode, have performed adequately in accelerated aging studies at the CERN GIF test facility at rates much higher than expected for the ILC. However, both sets of RPCs have demonstrated unexpected behavior indicating that there is more to learn about the long-term operation and performance of RPCs containing Bakelite. It is desirable to build RPCs using materials with better understood properties than linseed oil and Bakelite. Glass RPCs at BELLE have been reliable after initial start-up problems were solved, but are rate limited and very sensitive to the input gas humidity. New Bakelite RPCs developed for the BESIII muon system do not require linseed oil coating of the high-voltage surfaces and may prove to be more reliable than the traditional RPC style. Choosing the most reliable RPC technology for an ILC detector requires a thorough understanding of all aging issues and design problems.

Independent of the detector choice, some general design questions must be answered before an ILC muon system can be specified. The number of active layers, resolution, segmentation, and size directly affect both the cost of the detector and flux return steel as well as the performance.

Muon system simulation and design

R&D for the SiD Muon system should include a long-term simulation effort to characterize and optimize the detector performance. Simulation efforts will work within the Linear Collider Simulation framework[1] (org.lcsim – a Java-based reconstruction and analysis package, and SLIC a Geant4-based detector simulation package for the Linear Collider) to develop muon analysis packages and detector models. Both stand-alone (using only muon system information) and integrated (adding calorimeter and other sub-detector information) muon identification algorithms will be developed within this framework. These algorithms will be used to study muon ID performance as a function of the number of detector layers and detector resolution to help specify the final muon system design. Since the SiD calorimeter is <5 λ thick, the muon system may serve as a useful tail-catcher calorimeter. Studies of the calorimeter jet energy resolution with and without muon system information will determine if this option should be pursued.

It is expected that several different detector technologies would make adequate muon system detectors. Initial studies should be generic in approach and concentrate on defining the general detector parameters - resolution and minimum number of layers needed to optimize muon identification. After the technology choice, studies can be focused on the preferred technology to optimize both the detector and steel flux return design. Realistic background estimates and detector efficiencies will be implemented as the simulation effort matures.

The only significant study of muon identification for the SiD detector[2] was made by C. Milstene of Fermilab. As shown in Fig. 1, the purity of a sample of muons identified in $b\underline{b}$ jets at 500GeV/c^2 improves from 69% to 94% if information from the muon system is used to aid the calorimeter. The efficiency also improves in this study because the muon

[1] http://lcsim.org
[2] C. Milstene. "Muon Simulation", VLCW06 Vancouver, Canarda.

candidates must reach the indicated depth before being included in the efficiency denominator. This study should be repeated. The efficiency and purity will be studied as a function of track momentum for both barrel and endcap tracks.

Experience with the BaBar muon identification algorithm suggests that the number of interaction lengths penetrated by the muon candidate will be the most powerful discriminant between muons and hadrons. Other variables that will aid in hadron rejection are the average number of hits per layer along the track through the calorimeter and muon system, the goodness of the track fit, the pattern of energy deposition along the reconstructed track, and the fraction of layers hit. Algorithms with these variables will be developed and applied to various alternative muon system designs.

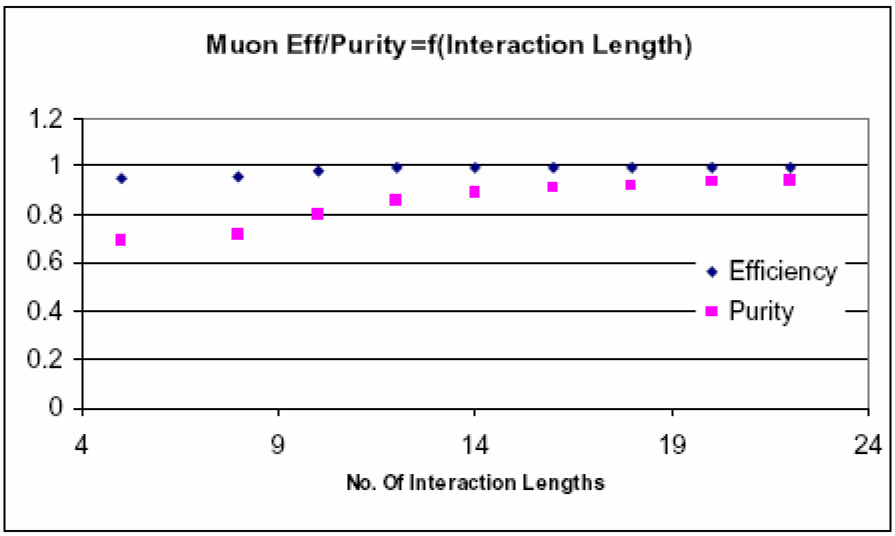

Fig. 1. Muon efficiency and purity versus the number of interaction lengths of the hadron calorimeter plus muon system for a muon identification algorithm developed by C. Milestene of Fermilab. The muon purity increases from 69% if only the calorimeter information is used (4.2 λ) to 94% (if most of the coil and muon steel is penetrated) in a sample of b$\underline{b}$ jets @ 500GeV/c^2.

The radial thickness of the detector steel will be set by the flux return requirements and not by the muon system. The number and thickness of the detector layers, however, will determine not only the total detector area (and cost) but also the total steel weight and cost. The first simulation goal will be to determine the minimum number of detector layers needed for a robust muon ID algorithm. Further studies will determine the needed detector resolution. In subsequent years, the simulations should become more realistic by including detailed detector geometries, beam backgrounds, and the effects of detector inefficiencies.

Simulation efforts to date have been severely manpower limited. Definitive studies in a timely manner are needed for a conceptual detector design. A postdoctoral researcher (50% effort) working with the senior staff is needed to help make the basic studies of the system and to develop the software algorithms in FY07/8. The simulation effort should ramp up in FY08/9 with the addition of collaborators or junior-level researchers and reach a steady level of effort for FY09-FY10 until the SiD TDR is written.

RPC Studies

A multi-pronged study of RPC technology is proposed for use in the hadron calorimeter and muon systems.

Goals:

- Validate the use of the KPIX front-end chip for RPC readout.
- Measure and predict the aging characteristics of the BESIII-type Bakelite RPCs to establish them as alternatives to standard glass or Bakelite RPCs.
- Gain experience with glass RPCs while studying possible aging mechanisms.

Wisconsin will collaborate with the SLAC KPIX group to test prototypes of the SiD KPIX front end data acquisition chip in the readout of RPCs operating in the saturated avalanche mode. The SLAC group will provide several KPIX chips for testing and aid in the design of a chip carrier that will mate to the ~ 3cm wide pickup strips of the RPCs. Initial tests of the device with existing Bakelite RPC chambers will establish the compatibility and robustness of the present design with actual RPC signals. If successful, the tests will be extended to glass RPCs as used in the HCAL prototype and to chambers constructed from BESIII Bakelite.

A second study will examine the production and absorption of F- (HF) in glass and BESIII RPCs and compare them to standard RPCs with linseed oil. Previous studies have found clear correlations between contaminants such as HF and increased noise rates and currents. Bakelite RPCs have been found to be sensitive to both the input gas and environmental humidity. A study of the humidity sensitivity of RPCs constructed from BESIII Bakelite will help determine the optimal operating conditions for these chambers.

In later years, study of alternative RPC gases could identify gas mixes that would minimize the production of harmful contaminants which lead to premature chamber aging.

1. KPIX Prototype tests

The KPIX chip containing 1024 ADC channels has been designed to readout the SiD electromagnetic calorimeter. The pulsed power chip will make up to 5 samples per ILC beam train. Use of the chip in other SiD systems has been encouraged. Application of the KPIX to muon system RPCs has raised several issues on compatibility. The pickup strips used on RPCs are large ~300cm^2. Natural channels counts per RPC are < 100, making the 64 channel KPIX prototype a better choice. It will also be desirable that the muon DAQ system collect cosmic rays between ILC pulses to monitor the RPC efficiencies. Extending the live time of a 1000 channel KPIX chip would require significant cooling. However, a 64 channel device should be capable of much higher live times.

We propose to build a 64 channel KPIX chip carrier which can be connected to existing RPC strips by commonly used 17-pair ribbon cables [A more optimized design would be developed after selection of the muon system technology]. RPCs instrumented with KPIX chips would be tested in the reconstituted Wisconsin cosmic ray test stand at SLAC using spares from the BaBar detector. Measurements of pulse height, cluster size, efficiency, and noise rate with cosmic rays would be compared to the existing test stand electronics (Flash ADCs, scalars and latches).

The test stand will have the capability to test 6-10 large (> 1 ×1 m) RPCs, well beyond the present need. Four reference RPCs will be used to trigger the DAQ and to define a cosmic ray track. Two RPCs with the KPIX readout chip will be sandwiched between the reference RPCs and read into a common data stream recorded directly to a PC hard disk. Modest upgrades to the test computer, monitoring, and DAQ are desirable. A half-time postdoc position starting at the end of FY07 will implement the test stand DAQ software and support data taking. Several bottles of premixed RPC gas will be needed per month of operation. If initial tests of the KPIX chip are promising, we would like to procure 5 glass and BESIII-type RPCs (~1 meter square) for further tests.

Aging Studies

Resistive Plate Chambers (RPCs) are likely technology choices for the SiD hadron calorimeter (HCAL) and MUON systems due to their low cost. RPCs have often been used as muon detectors (BaBar and BELLE) and will be used in both LHC experiments. RPCs are inexpensive to build and can be easily constructed in a variety of shapes and sizes. The major concern with RPCs has been their aging characteristics (BaBar was forced to replace its original RPCs and BELLE had startup problems). Despite the significant progress made in recent years in RPC R&D, a full understanding of all aging mechanisms has not been reached. For example, the precise role of gas contaminants such as HF (acid produced by the breakdown of the Freon used in RPC gases) in initiating "hot spots" and increased current remains to be understood. A thorough understanding of the physics and chemistry of RPCs is needed if this technology is to be chosen for use in an ILC detector.

Glass RPCs running in saturated avalanche mode are being considered for the SiD HCAL. A large (40 m^2 of RPCs) prototype system is being proposed for beam tests in FY08. The construction schedule for the prototypes is ambitious and leaves little time for further studies of possible aging effects or of alternative gas mixes. A smaller parallel effort could focus solely on these details and would broaden the US expertise in this potentially vital technology.

Recently an attractive alternative to glass has emerged from R&D for the BESIII muon system. The BESIII have developed Bakelite RPCs that have thin plastic films covering the inner Bakelite surfaces which eliminate the need for the traditional linseed oil coating. This new material has intrinsically lower noise than the Bakelite/melamine electrodes used in both the LHC and BABAR detectors. Over 1000 chambers were built and installed for BESIII. The bulk resistivity of the Bakelite can be adjusted to allow higher rate capability than glass. The BESIII chambers operate in streamer mode. Studies of these chambers in saturated avalanche mode while monitoring the humidity and HF content of the output gas may prove this design to have significantly superior aging properties than standard RPCs.

Broader Impact

The RPC tests described will deepen our understanding of RPC aging mechanisms and well hopefully lead to more reliable performance. Any improvements in RPC design or operation are applicable to RPC use in other applications such as the Daya Bay cosmic ray veto or the muon systems in the LHC detectors ATLAS and CMS. RPCs may possibly be used as detectors in Homeland Security monitors of industrial shipping containers.

Results of Prior Research

SiD Muon System Design Studies

Studies[3] have tried to estimate the cost of design decisions such as the number of detector layers or the thickness of the gap into which the detectors are inserted. Clearly the detector cost scales with area, however, the impact on the total weight of the detector is less obvious. If the total radial thickness of the steel is set to 3.2 m by the requirement to contain the return flux, the dependence of the total steel weight on the gap size or number of layers can be calculated as in Table 1. The total steel weight grows by 5.4% per cm of gap thickness. Reducing the number of layers from 23 to 14 reduces the detector weight by 500 metric tons, a cost savings of > 1.5 million $ if the cost of steel is 3.5$ /kg.

Other studies have estimated the average efficiency of one and two-layer RPC designs if the dead area due to edges and gas hoses is taken in account. For a single-layer design built from RPCs with a nominal efficiency of 90%, the average layer efficiency varied from 78-82% depending on the layer size. A double-gap RPC would have an average efficiency of 93%.

Gap cm	0	3	4	5	← 23 gaps	3	4
R_out m	5.63	6.32	6.55	6.78	14 gaps →	6.05	6.19
Barrel Metric tons	3011	3253	3334	3414		3182	3239
Endcap Metric tons	3776	4758	5111	5476		4360	4564
Total Metric tons	6787	8011	8445	8890		7542	7833

Table 1. The expected weight and size of the SiD flux return steel as a function of the thickness of the gaps between the steel layers. The total radial steel thickness is set to 2.3 meters to return the flux of the 5T solenoid. The yellow portion assumes 23 detector layers. The green portion assumes 14 layers.

[3] H. R. Band. "RPC Muon Option for SiD", VLCW06 Vancouver, Canarda.

BABAR Instrumented Flux Return

The BaBar Instrumented Flux Return (IFR) detector system consists of over 2000 m^2 of Resistive Plate Chambers (RPCs) which are inserted into the gaps of the flux return steel.
BABAR was the first experiment to use bakelite RPCs as a main detector in a colliding beam experiment. Unfortunately, the bakelite RPCs have experienced many problems due to a variety of causes (excessive linseed oil, poor quality control, aging of the graphite coating, gas leaks) which have lead to steadily decreasing RPC efficiencies in the barrel and backward endcap. The RPCs in the forward endcap were replaced in 2002 as part of an upgrade which also increased the amount of absorber in the forward region from 4 to > 6 λ. The new RPCs were built in Italy under a stringent Quality Assurance program developed by the BaBar IFR group. Many of these QA improvements were adopted by the LHC detectors (CMS and ATLAS) which produced their bakelite RPCs at the same factory. The performance and aging of these new BaBar RPCs is thus of special interest to the worldwide RPC community. The upgrade and aging studies were documented in three NIM publications in 2005[4,5,6] and several talks by H. Band at IEEE06, RPC2005, and IEEE03[7,8,9].

Although the new forward RPCs have performed well (the average RPC efficiency fell from 93% in 2002 to 92% in 2006) maintenance of the system has required constant activity and improvements to counteract several different problem areas. The forward RPCs experience widely different background and luminosity-driven singles rates (0.01 – 20 Hz/cm^2) depending on position within the endcap. The highest rates are centered around the beam-line in the inner layers. Starting in 2004, efficiency losses were seen in these regions. More relevant to an ILC muon system (expected background rates < 0.1 Hz/cm$^{2)}$ is the performance of BaBar RPCs in positions with low background rates (<2 Hz/cm^2). In four years of operation these low rate RPCs still have an average efficiency over 95% as shown in Fig. 2.

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[4] F. Anulli, R. Baldini, A. Calcaterra, R. De Sangro, G. Finoccgiaro, P Patteri et al. "BaBar Forward Endcap Upgrade". Nucl. Instr. Meth. A 539(2005)155-291.
[5] F. Anulli, R. Baldini, A. Calcaterra, R. De Sangro, G. Finoccgiaro, P Patteri et al. "Performance of second generation resistive plate chambers". Nucl. Instr. Meth. A 552(2005)276-291.
[6] S. Foulkes, J. W. Gary, B. C. Chen, K. Wang, R. Boyce, R. Messner et al., "Gas System Upgrade for the BaBar IFR Detector at SLAC" Nucl. Instr. Meth. A538(2005)801-809.
[7] H.R. Band. "Aging Studies of 2nd Generation BaBar RPCs". 2006 IEEE NSS Conference Record.
[8] H.R. Band. et al. "Experience with BaBar Resistive Plate Chambers". Nucl.Phys.Proc.Suppl..158:139-142,2006.
[9] H.R. Band. "Experience with BaBar Resistive Plate Chambers". 2003 IEEE NSS Conference Record.

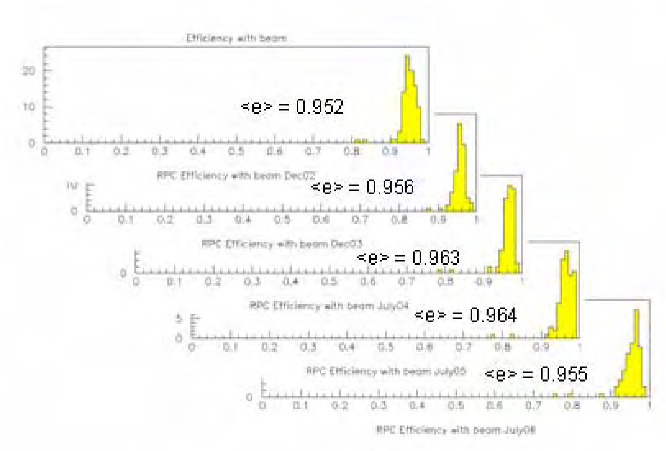

Fig. 2. Efficiencies of BaBar RPCs in positions with the lowest backgrounds at Dec. 2002, Dec. 2003, July 2004, July 2005, and July 2006 measured by μ pairs in data.

Inefficient regions also developed where the gas entered the chambers. Measurements showed that although the input gas was dry, the output gas was at 20-30% RH. The gas dryied the Bakelite preferentially near the gas inlets, leading to an increase in the Bakelite bulk resistivity and at moderate background rates, the increased resistance lowered the chamber efficiency. A gas humidification system was tested on a subset of forward RPCs in 2005 and as shown in Fig. 3, after several months of humidified gas the efficiency was much improved. All of the Babar RPCs have been converted to operation with humidified input gas. Tests are in progress to determine the BESIII operational parameters.

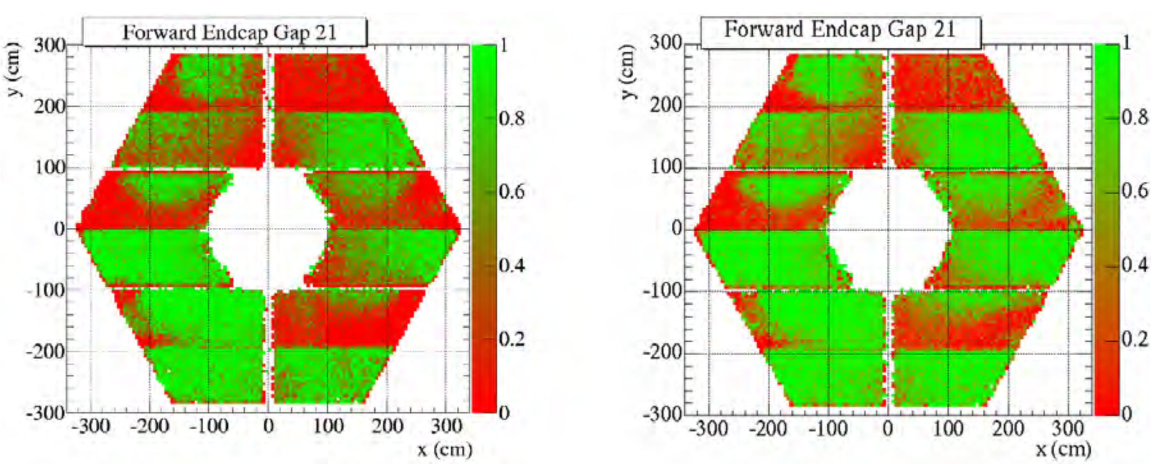

Figure 3. Two-dimensional efficiency of Layer 16 before and after 3 months of humidified gas.

The highest rate areas at small radii around the beam-line areas showed a progressive loss of efficiency with beam but not when measured by cosmic rays. One way to lower the rate sensitivity is to lower the amount of charge generated by each track or noise hit by changing the RPCs from streamer mode to saturated avalanche mode as used in the LHC RPCs. In collaboration with C. Lu of Princeton, 3 RPC chambers were tested by H. Band in avalanche mode in 2005. The chambers utilize a different gas mixture, separate high voltage control, and require pre-amplification of the RPC output pulse. Fig. 4 shows the efficiency versus radius before and after the avalanche mode conversion. Tests to date are very encouraging.

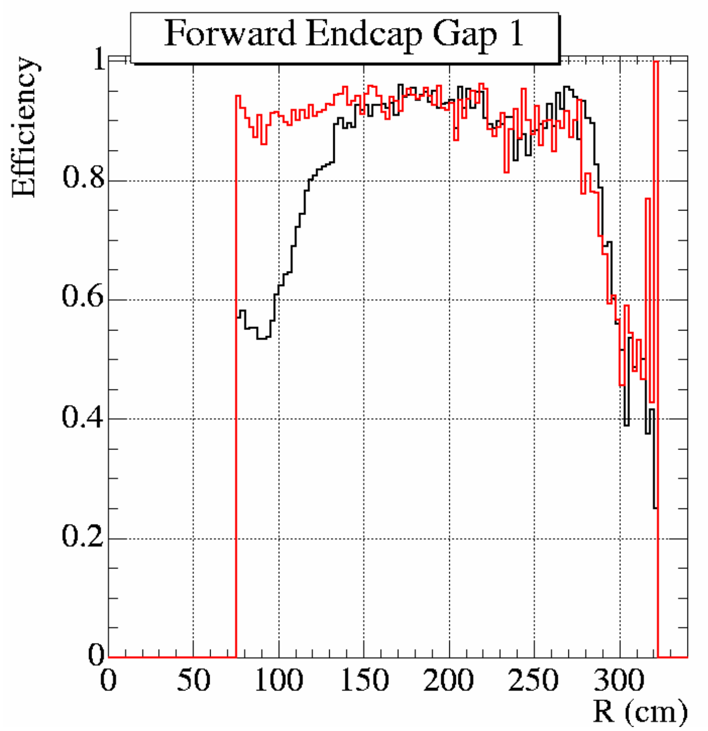

Fig.4. RPC efficiency as a function of R when the middle east chamber of layer 1 was operating in streamer mode (black) and in saturated avalanche mode (red).

Some of the BaBar observations of RPC aging[2] suggested that pollutants produced in the gas in the highest rate areas were being transported to other regions and producing increased noise rates. One candidate for a gas-born pollutant is HF which can be produced by the disassociation of the Freon component in the RPC gas. F^- ions in the RPC exhaust gas have been measured by ATLAS RPC aging studies[10] and by BaBar[11]. The RPC exhaust gas was bubbled through a mixture of TISAB and water, and a fluorine-specific ion probe measured the F^- concentration as a function of time. No free F^- ions were measured in the RPC input gas. Studies showed that the F^- was collected with >95% efficiency. Other studies measured the acidity of a water solution versus time and found that the measured F^- ions in the RPC exhaust gas were consistent with HF production .

The lower charge per track of RPCs operated in avalanche mode compared with RPCs operated in streamer mode suggests that less F^- is produced in avalanche mode. Measurements were made of the F^- production rate in two typical RPCs, one operating in

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[10] G. Aielli et al. "F^- ions Production in RPC Operated with Fluorine Compound Gases" presented at the "VII Workshop on Resistive Plate Chambers and related Detectors". Clermont-Ferrard, Oct., 2003.

[11] F. Bellini. "Fluorine Studies on the BaBar RPCs" presented at "RPCs@GIF Final Meeting". Geneva, Nov., 2004

streamer mode and the other operating in avalanche mode. Since the F^- rate depends on the chamber noise rate, the amount of F^- production in a day is plotted against the integrated RPC HV current in Fig. 5 for the two RPCs. The F^- production rate for the streamer chamber was 1.42 ± 0.11 μmole/Coulomb. The F^- production rate for the avalanche chamber was 3.82 ± 0.23 μmole/C. The avalanche chamber produces more F^- per unit charge than the streamer chamber. However, since the average charge per track is 4 times less for the avalanche RPC, the relative F^- production rates for streamer and avalanche RPCs were found to be similar. The rate of F^- production scales linearly with the detector current as expected. Studies of the fraction of F^- absorbed by the inner Bakelite surfaces are in progress.

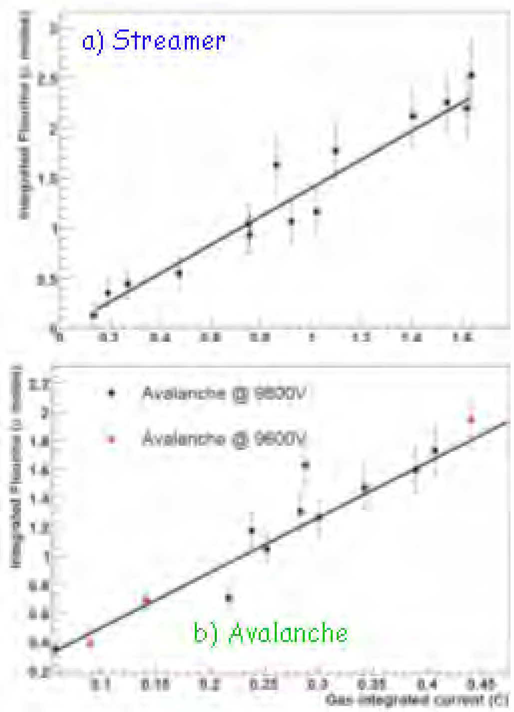

Fig.5. The integrated fluorine production in micromoles per day is plotted against the integrated HV current for that day. The current is corrected for bulk resistance effects to represent the current due to the gas gain. The streamer data in a) are fit by a linear dependence of 1.42 ± 0.11 micromole/C. The avalanche data in b) are fit by a linear dependence of 3.82 ± 0.23 micromole/C.

BaBar Muon ID

Under the leadership of H. Band, members of the Wisconsin group (I. Iakolov, A. Mohapatra, J. Hollar, K. Flood, and H. Band) have developed and maintained a neural net (NN) muon identification algorithm[12] that has become the recommended BaBar standard, replacing previous cut based and likelihood identifiers. A plot of the NN performance between 2000 and 2005 is shown in Fig. 6. The NN algorithm has a higher efficiency at fixed pion rejection rates than the cut-based algorithm. Also evident are the performance improvements from the endcap upgrade and shielding wall installation. Development work has continued on muon particle identification. Improvements in the underlying IFR

[12] A. Mohapatra and H. Band, “A Neural Net Algorithm” BaBar Analysis Document 333, 2004.

reconstruction code and fine-tuning of the neural net cuts as a function of momentum and theta have resulted in significant increases in muon efficiency. The use of present NN muon selector increases the relative efficiency for di-muon signal in the B->K(*)l^+l^- analysis by ~30% with no increase in hadronic backgrounds.

K. Flood has explored new methods beyond neural networks for optimizing muon identification. The most promising of these are boosted decision trees, which allow seamless integration of measurements from all detector systems in a single algorithmic framework. Unlike neural networks, the performance of decision trees is robust in the presence of incomplete data, improving the selector performance in the BaBar barrel, where many of the original RPCs have died.

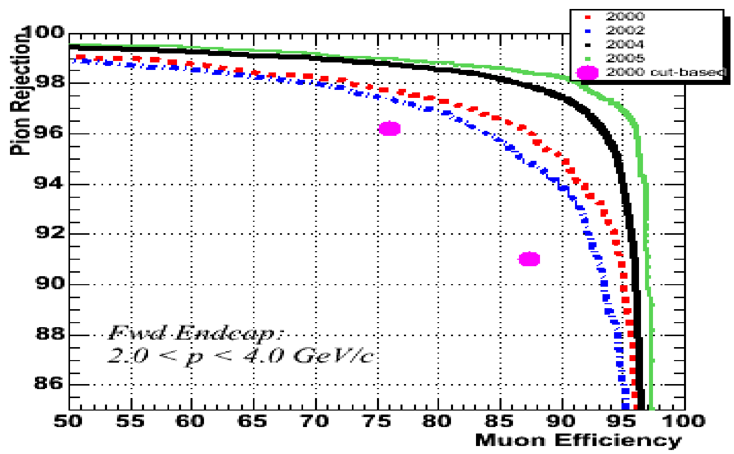

Fig.6. The performance of BaBar neural net and cut-based muon identification algorithms is plotted for several run periods. The higher the pion rejection (in %) at fixed muon efficiency, the better the algorithm. The NN reduces the pion mis-identification by a factor of two when compared to the cut-based algorithm in 2000. Also shown is the improved performance due to the endcap upgrade discussed in previous sections, which replaced RPCs and added additional absorber in 2004. Installation of the beam shielding wall prior to 2005 allowed routine use of the outermost RPC layers, further improving the pion rejection in 2005.

Facilities: Equipment and Other Resources

The proposed RPC studies would take place at SLAC which offers two essential advantages. The RPCs in the running BaBar experiment generate large amounts of fluorine and possibly other containments in the RPC exhaust gas which can be used in planned fluorine absorption experiments. We also plan to run a few test RPCs in the high rate BaBar environment(as we have done in the past) to test fluorine production versus gas flow, voltage, efficiency, and temperature.

The second unique SLAC resource is the Wisconsin/SLAC RPC test stand that we plan to rebuild for these tests. Approximately 50% of the electronic components are Wisconsin owned VME data acquisition cards. However, the other half are BaBar spares which cannot be removed from SLAC during until the end of BaBar data taking. These BaBar spares include CAEN high voltage crates and modules, general monitoring cards and gas distribution systems. The other essential BaBar items are thespare RPCs which are needed to fill most of the test stand. The BaBar RPCs will generate the cosmic ray trigger, and form the basis of the reconstructed cosmic ray track in software. The resolution of the BaBar RPCs is ~ 1 cm, adequate to make two-dimensional efficiency studies of the RPCs under study.

In addition to other infrastructure support, SLAC offers extensive technical expertise and shop facilities.

FY2007 Project Activities and Deliverables

Muon system simulation and design

The simulations should deliver by the middle of FY08, definitive studies on the main design questions posed above to support the design choices proposed in the conceptual design report.

- Develop stand-alone muon identification algorithm in the SiD framework.
- Determine the required detector resolution and number of detector planes.
- Estimate the effect of adding a muon tail-catcher on the calorimeter energy resolution.

RPC Studies

- Rebuild cosmic ray RPC test stand.
- Test KPIX chips using existing Bakelite RPCs operating in saturated avalanche mode.
- Measure the production and absorption of HF in linseed oil RPCs and BESIII RPCs.

Project Activities and Deliverables Beyond FY2007

Muon system simulation and design

FY08/9 Milestones

- Optimize muon detector and flux return design.
- Implement detailed Monte Carlo geometries.
- Develop integrated muon identification algorithms initially incorporating both the calorimeter and muon systems, with the ultimate goal of incorporating all detector information.
- Add background noise and detector inefficiency to MC.

FY9/10 Milestones

- Optimize algorithms for preferred technology.
- Provide studies and plots needed for the SiD TDR.
- Verify robustness of muon ID algorithm against possible detector problems or expected backgrounds.

RPC Studies

FY08/9 Milestones

- Complete fluorine and aging studies on standard Bakelite RPCs.
- Acquire ~1 m^2 glass and BESIII RPCs to extend both the KPIX readout tests and aging tests.
- Develop SiD specific RPC designs.

FY9/10 Milestones

- Build double-gap chamber prototypes for muon system.
- Study alternative gas mixtures.
- Document SiD RPC design for TDR.

Budgets

M&S

Funds to design and procure KPIX chip carriers and other electronic components necessary for use in the RPC readout (~15k$) are requested. Requested upgrades of the test stand DAQ total ~15k$ for a VME crate, Struck VME to PCI-bus control card, PC, and LabView program. Consumables (gas) and replacement fluorine probes (~2 year lifetime) for 15k$ complete the request.

Manpower

Support for the equivalent of a F.T.E. postdoctoral position is requested. A single postdoc could work half-time on the simulation and half-time on the RPC studies. It may be more reasonable to share postdocs with either the Wisconsin BaBar or CMS analysis Tasks. This would introduce young physicists to the ILC while giving them a chance to work on a physics analysis.

There are 3 ILC meetings per year (two abroad and 1 US) and typically two other workshops (SiD or subsystem). Funds are requested for three foreign and 4 domestic trips to present research results and to participate in detector planning discussions.

The University of Wisconsin fringe rate on postdoctoral salaries is 25%. Overhead costs for off-campus projects are 26%.

Total Project Budget, in then-year k$

Item	**FY2007**
Other Professionals	0
Graduate Students	0
FTE PostDoc	50
Total Salaries and Wages	50 k$
Fringe Benefits	12.5 k$
Total Salaries, Wages and Fringe Benefits	62.5
Equipment	30k$
Travel	15k$
Materials and Supplies	15k$
Other direct costs	0
Total direct costs	122.5k$
Indirect costs	24.050k$
Total direct and indirect costs	146.550 k$

Appendix

Appendix: Participation Data

Funding requested by detector proposals	FY07
Luminosity, Energy, Polarization total	$847,922
Vertex Detector total	$217,413
Tracking total	$805,728
Calorimetry total	$2,499,556
Muon system total	$357,550
Total	$4,728,169

Number of projects in this document	N
Luminosity, Energy, Polarization total	9
Vertex Detector total	4
Tracking total	10
Calorimetry total	14
Muon system total	3
Total	40

Participation by institutions	N
U.S. Universities	37
National and industrial laboratories	6
Foreign institutions	36
Total	79