Scintillator Based Muon System R&D: 3-Year Proposal

Subsystem: Muon and Particle ID

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Project Overview

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 15 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 ILC 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 7 or more planes and absorber will be operated in a test beam. Because the muon system is the largest one in the ILC 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.

The close collaboration between the institutions requesting funding and Fermilab is described in detail in this proposal. Other collaborating institutions are also involved.

Northern Illinois University will continue to work with us on source testing of scintillator, simulation software and software infrastructure. We will closely follow NIU's independent work on scintillator extrusion and coating and the application of silicon photomultipliers for fiber readout. The UCD group will work with Fermilab to develop a common solution for front-end electronics and data acquisition.

Indiana University will help us test the 1m X 0.5m prototype module at Fermilab. The University of Texas at Austin will continue to provide us consultation about MAPMT's based on their experience with MINOS.

Colorado State University is developing geiger mode avalanche photodiodes and will test their devices with our prototype modules. In addition, the CSU group will participate in the overall muon system development.

Rice University is not currently active, but intends to work on this project in the future.

We also keep abreast of the work led by of Marcello Piccolo of Frascati on resistive plate chambers and muon simulation which is complementary to this work.

Broader Impact

The work outlined in this proposal, if supported, will have an educational impact at several levels. Many of the projects described will be carried out at the universities, and thus are good matches for undergraduate and graduate student participation. Over the past year, both a sophomore physics major and a first year graduate student have helped with the fiber R&D at the University of Notre Dame. So far, one undergraduate and one graduate student each at WSU and two graduate students and three undergraduates at UCD have participated in this effort at various times. Research and development projects like this muon detector proposal are particularly beneficial for student training, since most of the U.S. particle physics program is currently focused on either data analysis of existing experiments, or the construction and commissioning of the LHC experiments at CERN.

In terms of even broader educational outreach, each of the lead institutions on this proposal supports a QuarkNet center, and Prof. Wayne is currently one of four co-principal investigators of the national QuarkNet program. These centers are firmly established as communities of scientists and educators that engage in a wide range of activities. The QuarkNet centers offer direct research involvement to high school students and teachers, and often provide a "hands-on" experience for people from traditionally underrepresented groups. A high school teacher has been very active in this research at WSU under the QuarkNet program. Several of the projects making up this proposal are ideally suited for student/teacher participation. The high school teachers and students affiliated with Notre Dame and WSU will certainly be involved in the fabrication of muon detector planes during the upcoming summer.

Some of the university groups also participate in NSF-sponsored REU programs, and we expect that at least a few undergraduates will work on the muon system for their research projects this summer. The REU program at UCD is in its second year. We expect to recruit students to work on the muon test-stand during the summer.

While the focus of this effort is towards research in experimental particle physics, the results of this type of R&D often find application in other areas. Scintillator based detectors are used in a wide range of areas. The detection and timing of very small light levels is of interest to many fields, both in basic research and in the private sector. There has been a great deal of interest recently in the potential use of particle physics detection techniques to enhance our national security. Of particular interest is whether very large detector arrays, like our muon system, can be used as efficient, cost-effective tools to monitor the safety of large items transported into the country (e.g. containers brought in by ship)

Results of Prior Research

During the past year, a collaboration of Fermilab, UC Davis, NIU, Notre Dame and Wayne State has worked to understand the scintillator-based ILC Muon detector hardware issues and to pursue those issues with the priority and manpower that is possible with the limited funding for the universities presently involved. Fermilab, which requests no funds from this proposal, has separate funding for ILC detector work: $45K in material costs during FY04 and approximately an equivalent amount in technician and engineering manpower support. We expect continued support from Fermilab.

The University of Notre Dame group, led by Mitch Wayne, has focused on the mechanical design and construction of the muon detector planes. As described above, the muon detector is comprised of large planes of scintillator strips, each with a green waveshifting fiber embedded along the length of the strip. The waveshifting fibers are in turn connected to identical clear fibers that pipe the light to the photodetectors, in our case multi-anode photomultiplier tubes (MAPMTs). A key element of our design is that each waveshifter-clear fiber connection is done individually with a thermal splice. This simplifies the mechanical design of the detector planes and the routing of the clear fibers to the PMTs. Thermal splicing also eliminates the need for complicated connectors.

The WSU group consists of P. Karchin (faculty), A. Gutierrez (research engineer) and R. Brockhaus (high school teacher). A. Gutierrez has 9 years experience with electronics and computers in HEP, including work on CDF, ILC R&D, HERA-B, CLEO and B-TeV. R. Brockhaus is a science teacher at Mumford High School in Detroit and works with WSU as part of the QuarkNet program. In previous years, a graduate student and an undergraduate student have worked on the ILC muon project. The WSU group has concentrated on the overall coordination of the scintillator-based muon collaboration (P. Karchin is co-coordinator with H. E. Fisk) and the application of MAPMTs as the optical detectors.

The relatively low per-channel cost of the Hamamatsu MAPMT provides a cost-effective readout that allows for reasonable granularity of the scintillator elements. Furthermore, MAPMTs are reliably produced by a commercial manufacturer and are well established in running HEP experiments, such as MINOS (near and far detectors) and CDF (end-plug calorimeters and central pre-shower detectors). Thus, the MAPMT is an excellent candidate for a full-scale ILC muon detector and also serves as a well-understood detector to measure the response of prototype scintillator/fiber detector elements.

The UCD group, led by Mani Tripathi, has focused on the readout electronics aspect of the project. The electronics shop at UCD has been developing readout electronics for HEP for the last

3 decades. Juan Lizarazo, a graduate student in both physics and electrical engineering, has worked on several HEP projects including CACTUS and D0, where he was a visiting engineer for two years. During FY03, the UCD group developed large bandwidth amplifiers for 16-channel MAPMTs. During FY04, a custom readout system using commercial TDCs and FPGAs was built by borrowing some components from PREP at Fermilab. Several undergraduate students have worked on this project over the last two years. Below we describe, in greater detail, the progress made by these groups.

Fermilab Most of Fermilab's development support has been in the area of scintillator and fiber procurement and tests, fiber splicing via thermal fusion, a PMT test setup at Fermilab in parallel with a similar setup at WSU to measure MAPMT properties, and the beginning of an involvement of Fermilab engineering in the evaluation of a scintillator readout scheme based on electronics originally designed for D0 scintillator fiber readout that has been prototyped for a possible future neutrino experiment.

In December 2003 Fermilab took delivery of 756 strips of 3.5m X 4cm X 1cm extruded (MINOS type) scintillator and 4.5/3 km of clear/WLS 1.2mm diameter fiber. During the manufacture of the extruded scintillator at Itasca Plastics in St. Charles, IL we had them provide a 1m long strip hourly so we could monitor the quality of the scintillator. We used 15 of these strips to do WLS fiber-gluing tests using various adhesives. Clear RTV-615C, Epon 815 and BC600 were each tested. Measurements by NIU personnel with a Cs^{137} source show that all three performed approximately equally well.[1]

The delivered scintillator and fiber is sufficient to build 8 single-layer planes of muon detectors 5m X 2.5m. The purpose of the R&D with planes was to establish a knowledge basis to insure that all technical, cost and physics implications were well enough understood to build an ILC muon system that would not only detect, track and identify muons, but that it could also be used to measure hadronic energy from late showering hadrons, i.e. as a backup calorimeter. While a size of 5m X 2.5m is sufficient to provide full coverage in the outer gaps of an octagonal Fe return-yoke 10m in length, by using 4 such planes per gap, test beam considerations, especially space limitations, have convinced us to begin with planes that are 2.5m X 1.25m. We call these planes the ¼ (sized) planes. In preparation for building the first four ¼ planes, a pre-prototype module 1m X ½ m was built at Notre Dame. It is presently under test at Fermilab. The focus of the pre-prototype was scintillator layout, gluing, fiber splicing, fiber routing, fiber bending, etc.

Instead of using fiber connectors to make the WLS-Clear connection we have chosen to thermally fuse clear-to-WLS fiber as discussed below in the Notre Dame section of this document. The splicing was done in Lab 7 at Fermilab where the method was first established for the CDF end-plug calorimeter.

In collaboration with WSU, a testing area was set up in Lab 6 at Fermilab for testing MAPMTs, scintillator and electronics. The setup is essentially identical with the one at WSU that is described below for measuring the gain of MAPMTs.

[1] see www.linearcollider.ca:8080/lc/vic04/abstracts/detector/muonpid/gene_fisk_new.ppt

In November ‘04 during discussions about readout electronics we learned that the Fermilab ASIC's project group has developed a 16 channel board, for a possible future neutrino experiment, based on a chip developed for D0 and the SVX chip, as discussed in the UC Davis section of this document that may be well suited to our application. Collaborative engineering on this board, with contributions from UCD and Fermilab, is now underway.

University of Notre Dame The UND group has worked in conjunction with Lab 7 at Fermilab to test the effectiveness of thermally splicing fibers together. In our first test, a total of 64 eight-meter long pieces of clear fiber were measured for light throughput before and after splicing. In our system, green LED light is injected into the near end of the fiber while the light exiting the far end is measured with a photodiode. The photodiode response is digitized and read into a computer. Our system utilizes a bank of 8 LEDs and 8 photodiodes, all intercalibrated to normalize their response. Most of the 64 fibers were then cut in half, polished and spliced back together at Fermilab. A small number were left whole to monitor any changes in our measurement system. When the spliced fibers were remeasured, the results were not satisfactory – there was a large spread in the light transmission from piece to piece. However, several splices did show good transmission of 90% or above. After some minor adjustments to the procedure, a second, smaller test was performed with acceptable results.[1] We are now confident that large numbers of fiber splices can be made with repeatable results.

One complication in fiber splicing is that both the waveshifting and clear fibers are stored on large, circular spools. This creates a residual curvature in the fiber, making it more difficult to precisely align the two faces of the fibers being spliced. Our group has developed a technique to straighten out the ends of the fibers using gentle heating. Concerned about potential damage to the fibers from the heating, we tested the light throughput of several pieces of both clear and waveshifting fiber before and after heating. To our surprise, the light throughput increased by about 10% for each fiber end that was straightened. This is an interesting and encouraging result that needs further study.

To help demonstrate the mechanical design and work through many of the fabrication steps, the Notre Dame group recently constructed a “pre-prototype” detector plane with scrap materials. Figure 1 is a photograph of the readout end of the module showing the routing of the clear fibers to the cookie mounted on the support frame. Also visible at lower right is the flat optical panel used for calibration. The cookies and calibration scheme are discussed below.

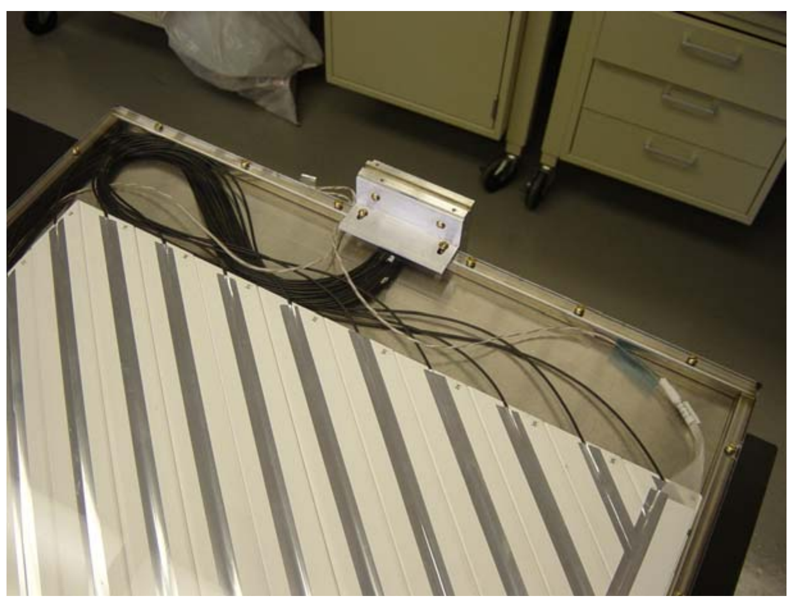

Figure 1: A photograph of the pre-prototype module.

Wayne State University The WSU group has developed a scheme to calibrate the single photo-electron response of a MAPMT using fast pulses from a light-emitting diode (LED). We used a 16-channel Hamamatsu H8711 MAPMT.[2] A clear fiber transmits light from an LED and is aligned to the photo-cathode face by an aluminum guide with an array of holes corresponding to the cathode pixel grid. A mass termination connector provides a transition from the anode pins to a miniature (RG174) coaxial cable. The single-shot digital oscilloscope trace in Figure 2 shows the voltage pulse driving the LED and the response from a single anode channel, for a high voltage bias of 850 volts. The anode response for this single primary photo-electron is seen to be narrow (width at half max is about 4 ns) with a peak amplitude of about 30 mV. Electronic noise is visible with peak-to-peak amplitude of about 8 mV. Tests with a high quality Faraday cage show that the noise can be reduced with improved electromagnetic shielding.

Charge spectra from anode pulses, initiated by the LED, were recorded with a LeCroy QVT. Spectra for three different high voltage bias values are shown in Figure 3. The spectra were analyzed under the assumption of Poisson statistics for the number of primary photoelectrons produced during a timing gate centered on the LED pulse. For 825 volts bias, the charges corresponding to 1 and 2 photoelectrons are indicated in the figure. The gain is measured to be about 23 x 10^6, consistent with data provided by Hamamatsu.

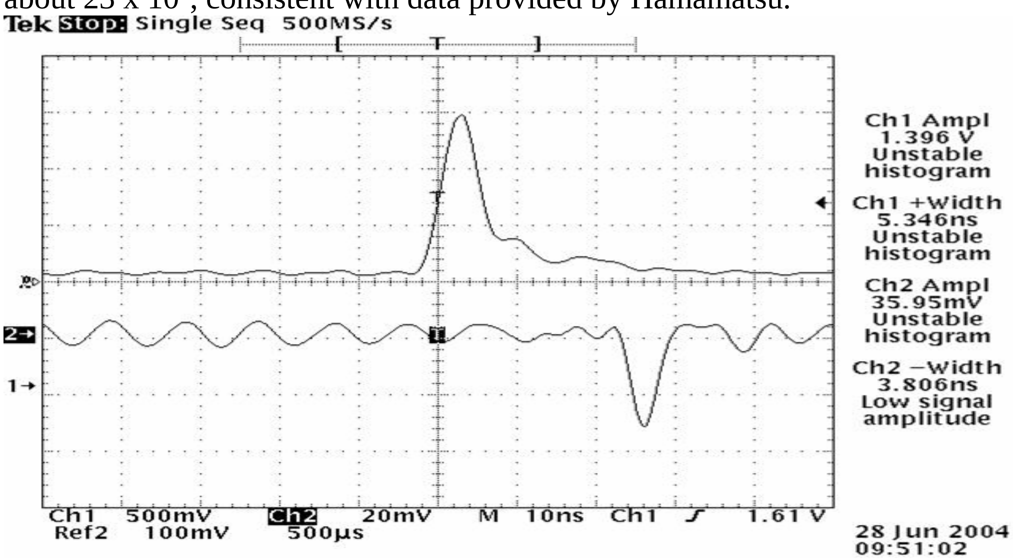

Figure 2: Single-shot digital oscilloscope trace for LED voltage pulse (top) and single anode response (bottom).

The technique presented here, using LED pulsing, can be used to calibrate the single photoelectron response. We plan to extend this technique for an in-situ calibration scheme, injecting LED light into the scintillator strips.

[2] For further details and a photograph of the MAPMT and associated components see the DPF 2004 paper by P. Karchin at http://physics.ucr.edu/~billdbrk/papers/paper214.ps and the talk by P. Karchin at the 2004 Victoria LC conference at http://www.linearcollider.ca:8080/lc/vic04/abstracts/detector/muonpid/paul_karchin_v2.ppt

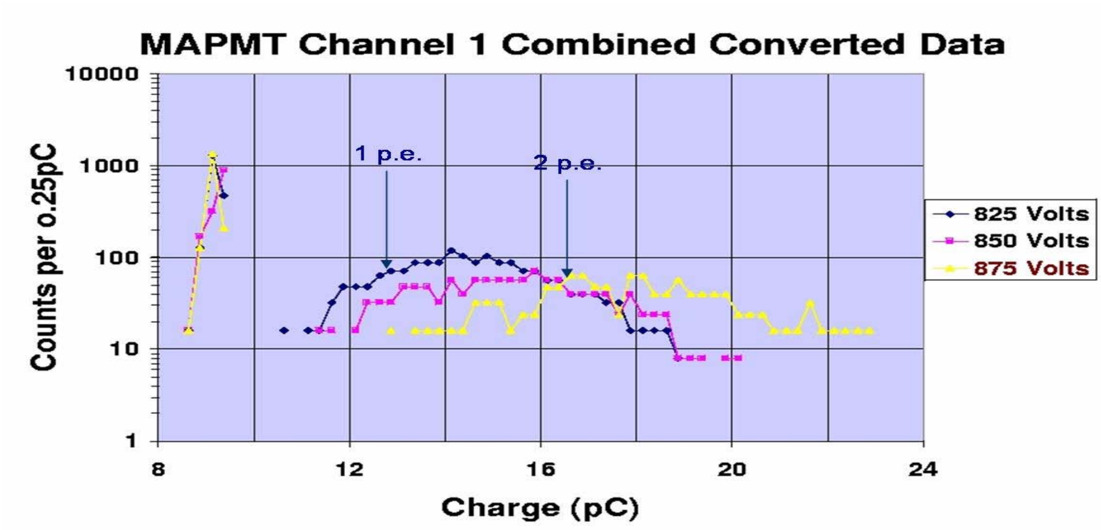

Figure 3: Charge spectra from anode pulses for three different cathode bias values. For 825 volts bias, the mean charges corresponding to 1 and 2 photoelectrons are indicated in the figure.

University of California, Davis During FY2004, the UCD group completed the development of a readout system for the prototype muon test-stand. This system, shown in Figure 4 in a schematic form, utilizes CAMAC modules that are on loan from PREP at Fermilab. Fast discriminators that are used to convert the analog signals to digital pulses preserve the time-over-threshold (TOT) information to better than 1 ns, while the TDCs record both the rise-time and the fall-time with a 0.5 ns resolution. This ability to provide dual-edge recording allows us to get a crude measurement of the pulse-height via TOT with an effective resolution of 20 mV/ns.[3] The wide bandwidth (~1.5 GHz) amplifiers that we had developed in FY2003 preserve the pulse from the MAPMTs to a high accuracy, thus giving us confidence in our ability to measure pulse-heights in a 1V dynamic range with an effective 5-bit resolution. The TDCs are read out from the front-panel ECL bus and fed into an FPGA which also provides trigger and control features. This Xilinx XCV1000 FPGA board, along with auxiliary boards for level-translation (ECL-LVDS and TTL-LVDS), was also developed at UCD. The data from the FPGA are read out into a Linux computer via the parallel port operating in the EPP mode, capable of providing 8 Mbps data transfer. The readout system was tested successfully on the bench with trigger rates exceeding 1 KHz.

[3] see: http://www.linearcollider.ca:8080/lc/vic04/abstracts/detector/muonpid/mani_tripathi.PPT

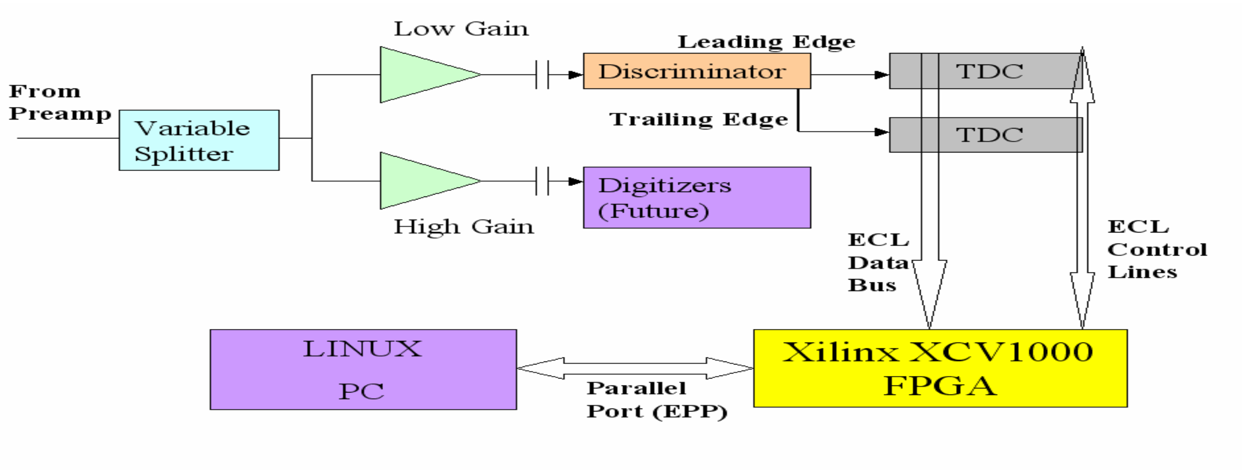

Figure 4: A box-diagram of the readout system that was developed at UCD for use at the prototype muon detector test-stand at Fermilab.

Muon Detector Software Development Caroline Milstene at Fermilab has developed muon tracking and identification software packages in the framework of the JAVA based JAS. This encompasses four areas: (1) rework of the tracking code that simultaneously takes into account both energy-loss and charged particle acceleration in the solenoid and Fe return yoke magnetic fields, (2) improved efficiency for matching low momentum muon candidates with upstream charged particles, (3) studies to predict fake rates partly due to punch-through of nearby charged hadrons in the barrel detector that satisfy the criterion for muon identification, and (4) initial study to implement Kalman filtering to provide greater analytical power in matching upstream tracks with muon candidates and thereby further reduce mis-identified punch-through.

Stepper Software/Low Momentum Tracking Efficiency Improvements The original projection of Monte Carlo charged particles through the tracking detectors and calorimetry into the muon system did not take into account dE/dx. This caused inefficiency in the matching of muon detector candidates that were generated via GEANT, which included the full detector geometry and materials (dE/dx, etc.), especially for muons below 10 GeV/c. The Stepper software (Fermilab TM-2274E) uses a matrix approach to simultaneously include dE/dx and q***v** x **B** effects in projecting central detector tracks into the calorimeters and muon detector. Excellent agreement is obtained between the projected and identified muon track candidates (14 hits in 14 layers for the SiD geometry) with the Stepper.

A "before" and "now" plot of projected and actual phi vs. layer number (radial depth) hits for a 3 GeV/c muon are shown in Figure 5, where "now" is with the Stepper software. The improvements in efficiency are shown in Table 1. The Ad-Hoc line in the table refers to a momentum-dependent enlargement of the (theta, phi) road that allowed improvement of the efficiency; the Stepper can be seen to further improve tracking efficiency.

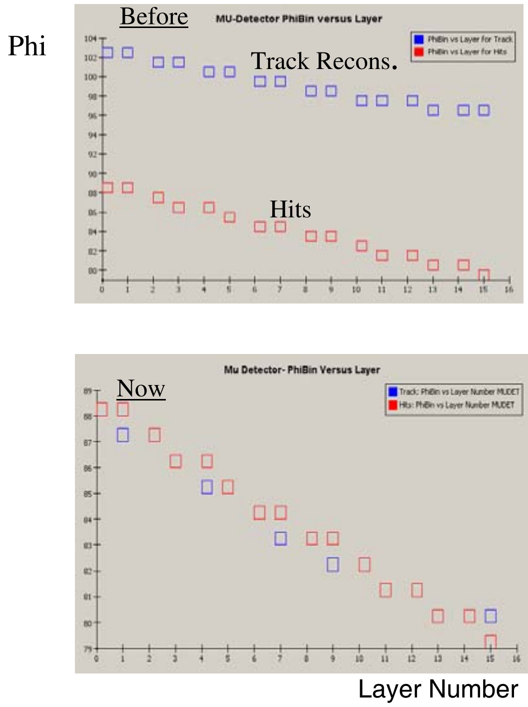

Figure 5: Improvements achieved with the Stepper software as described in the text.

E (GeV/c) / Technique	3	4	5	10
No dE/dx	0.06%	70%	97%	99%
Ad-Hoc dE/dx	23%	95%	97%	99%
V x B + dE/dx	33%	96%	99%	100%

Table 1: Muon Tracking Efficiency

<u>Muon Mis-identification and Hadronic Punch-through</u> In jets, the presence of many nearby particles provides a challenge that was studied with 10,000 b-quark pair produced events (20,000 b's). From the b-jets there were 18,666 (34% of the produced) π's, 4,473(54%) K's and 1,622 (58%) protons that had momenta (> 3 GeV/c) sufficient to penetrate the first 14 plates of the muon detector, assuming they ranged out before interacting. From these hadrons, 70 π's, 41 K's and 2 protons met the muon ID criteria. These numbers include12 π's and 3 K's that decayed to muons. Thus, the fake rate probabilities for π's, K's and protons, including punch-through, are 0.0037, 0.0092 and 0.0012, respectively, using the present Stepper algorithm. Because many of these 113 muon candidates have hits in the first four layers of the muon detector, but then meet the 14 layer hit-criterion using hits that belong to nearby muons or late interactions, a more sophisticated algorithm may make it possible to further reduce fakes due to punch-through.

<u>Kalman Filter</u> Work has started on the development of a Kalman filtering algorithm that will include track fitting as a way to eliminate extraneous hits from neighboring tracks

Facilities, Equipment and Other Resources

At the University of Notre Dame, several laboratory spaces are available for the work described in this proposal. These include rooms in the main physics building as well as a 5000 square foot off-campus laboratory. These spaces have been used for general fiber R&D and for the construction of clear fiber waveguides for the D0 central tracker. The Department of Physics also houses a full-service machine shop with a numerically controlled mill and lathe, a wire EDM, along with several more conventional machines. A LINUX cluster, SGI cluster and IBM RS6000 clusters are all available in the high energy physics area. Various PC's, Macs, SUN workstations and other terminals are also in use in offices.

At the University of California, Davis the electronics shop has capabilities for designing, simulating and laying out circuits using state of the art software tools. The fabrication is usually done by vendors in Silicon Valley but all of the testing is done in-house. The test lab contains a full suite of instrumentation for high bandwith analog signal analysis and debugging of multi-channel digital logic. The labs are also equipped with hardware and software for FPGA firmware development, VLSI chip design and probing of bare ASICs. A clean room and an electromagnetically shielded room provide space for testing sensitive components. A 32 node Linux cluster is available for large scale data analysis along with 3 TB of data storage space.

Wayne State University has both an electronics instrumentation laboratory and a machine shop which are used for the MAPMT work. There are also computing facilities which currently support the group's work on the CDF experiment at Fermilab and are available for use on the muon project.

The scintillator-based ILC muon detector R&D effort is supported by several Fermilab facilities and personnel. We are using the fiber splicing facilities and personnel, Eileen Hahn, in Lab 7. We have a PMT test area in the high bay of Lab 6 largely setup by Paul Karchin and Alfredo Gutierrez (Wayne State) and are presently testing our pre-prototype module in Lab 6. We sometimes make use of the PMT test area, set up by Hogan Ngyuen in Lab 6 and we have previously used a radioactive source and light-tight scintillator strip test box in Lab 5 that has now been moved to Lab 6. An engineer from UC Davis has worked with the ASICs Project Group/Paul Rubinov on the Minerva board in the High Rise and we expect this to continue over the next year or so. We infrequently make use of the Physics Research Equipment Pool and expect to continue to do so. We plan a more involved test area in Lab 6 and use of the MTest beam starting in about a year. We will make more use of Fermilab office space, computing and other facilities in the future.

FY2005 Project Activities and Deliverables

University of Notre Dame During the upcoming year, the Notre Dame group will lead the fabrication of 4, quarter-size muon detector planes, with dimensions 2.5 m by 1.25 m. These will be fully functional detectors based on our current design, with thermal splicing between the waveshifting and clear fibers. Each of the four planes is comprised of 64 scintillator strips. Two planes will be read out at one end, while the other two will have clear fiber readout from each end of the strips. The planes will have strips oriented with alternating 45^0 stereo angle. For both the single-ended planes and double-ended planes, each clear fiber will be read out by a separate pixel of a 64-channel Hamamatsu PMT. The final product will be a complete detector array of 4 planes which can be studied thoroughly in a test beam or cosmic ray telescope.

At Notre Dame we will cut the scintillator strips to appropriate lengths and at the correct angle. The strips are then glued onto a supporting structure to create the detector plane. Clear and waveshifting fiber will be cut to length and measured with our LED-photodiode system. Fibers with throughput below a pretermined value will be rejected. Once the requisite number of fibers are ready, their ends will be thermally straightened. The fiber ends will be finished at Fermilab with an ice polishing technique and then the clear and waveshifting fibers will be spliced together. The spliced fiber lengths will be transported back to Notre Dame, tested for light transmission, and glued into the scintillating strips. Notre Dame will design and fabricate “cookies” in which the clear fibers are terminated. These cookies must precisely align the clear fiber ends with the PMT pixels in a safe and light-tight manner. Our group will design the mounting scheme to mate the cookie to the PMT.

One important design feature is the calibration system. For these prototype detectors we propose a system using flat optical panels, a technique our group developed for the D0 fiber tracking detector. An LED injects light into the panel, creating a uniform ribbon of light approximately 20 inches long and 2 inches wide. By laying the panel across the strips, several channels can be illuminated simultaneously with a relatively well-controlled amount of light. This system will also be useful for debugging the detector readout and for monitoring performance over time. The panels are commercially available from Lumitex.

Wayne State University The WSU group will procure, test and calibrate enough MAPMTs to read out the 4 quarter-size prototype planes. This requires six 64-channel tubes or two 64-channel tubes in combination with two 16-channel tubes. The 16-channel tubes read out 8 fibers per pixel whereas the 64-channel tubes read out 1 fiber per pixel.

We will calibrate every MAPMT channel using the method developed in our previous work. In addition, we will establish procedures for in-situ gain monitoring using light injected into the scintillator bars. We will install and debug the tubes at Fermilab and participate in data taking and analysis using radioactive sources and cosmic rays. We will prepare written reports of our work and present it at conferences and/or publish it in journal form.

University of California, Davis While the readout system described above is good for debugging/calibrating MAPMTs and for reading out prototype planes, it cannot be scaled up for reading out a 512 or 1024 channel muon test-stand. For this purpose, we are proposing to work with a readout system that has been developed at Fermilab for the Minerva experiment. It utilizes a TriP chip, developed for D0, which combines the functionality of the SIFT and SVX chips. It is being developed for use in several Fermilab experiments. This board will not only provide 16 channels of amplification and discrimination but it will also be capable of storing the charge in an analog pipeline and subsequently digitizing the data with an 8-bit accuracy after receiving an external trigger. An FPGA is used to latch the time-of-arrival of the discriminated pulses with a resolution of about 2 ns. This is worse than the 0.5 ns provided by the CAMAC system, but it is expected that the accuracy will improve as FPGAs with higher clock frequencies become available. Moreover, the 8-bit digitization is vastly superior to the 5-bit information gained from the TOT technique. A prototype of this board exists but it needs several corrections before it can enter a production stage.

A UCD graduate student, Juan Lizarazo, has worked with Fermilab physicists and engineers to learn the circuit schematic and board layout. Copies of all of the electronic design documents now exist at UCD. During FY05, we will be developing a modified version of this board for our purposes, including the ability to mate 4 16-channel boards to a 64-channel MAPMT and providing some improvement to the time synchronization circuitry. The TriP chip has some problems in maintaining the thickness of the finished die which makes it difficult for automated wire-bonding. The UCD group will work with vendors to custom wire-bond 40 chips into plastic chip carrier packages. During FY05, we will provide 16 boards for the prototype muon test-stand.

The group at NIU is working on a tail-catcher for the ILC. We will work with them to ensure that there is commonality in the readout system and that the data from the beam test will have a common format.

FY2006 Project Activities and Deliverables

<u>University of Notre Dame</u> In the second year the emphasis will move towards the fabrication of full-size detector planes. Based on our experience in building and operating the 4 prototype detector planes, we will make any necessary design changes, and also concentrate on developing "assembly-line" production methods for the final detector. A large, clean work area and the infrastructure necessary to handle and transport large detector components must be developed.

The group also plans to help in the analysis of data collected with the 4 detector array. These results will be key in several final design decisions, including which PMTs to use and the multiplicity of fibers presented to each PMT pixel.

<u>Wayne State University</u> We will procure, test, calibrate and install additional MAPMTs to read out full-size prototype planes. Tubes from the quarter-size modules will be re-mounted on the full-size planes. The choice of additional 16 or 64 channel tubes will be made based on the results of the Year 1 tests.

We will participate in data taking at Fermilab with a test beam and contribute to the data analysis. We will prepare written reports of our work and present it at conferences and/or publish it in journal form.

<u>University of California, Davis</u> The long term plan is to develop 40 boards at a cost of $18K, or about $30/channel. The first year will be spent in developing the design and making a batch of 16 boards. During the second year, we plan to build a second batch of 16 boards. It is expected that there will be minor improvements made with this design. We will also implement a version of the data acquisition software that already exists for the Minerva experiment. We will send a graduate student to reside at Fermilab and help with the data taking and calibration of the prototype muon detector. The student will also help with analysis of the calibration data.

FY2007 Project Activities and Deliverables

University of Notre Dame By the third year we will be fabricating full-size detector planes. Cosmic ray and beam test measurements with these planes will provide important tests of the design choices. Assembly techniques will be optimized. Work will continue on integration of the muon detector with the rest of the detector systems.

Wayne State University We will complete the work for the full size planes described in Year 2. In all years, we will coordinate our work with the world-wide effort on specific detector designs. We will help evaluate the potential of novel light detectors such as geiger-mode photodiodes and silicon PMTs for use with a scintillator based muon detector. We will help provide cost estimates for readout of a full-scale ILC muon detector and help coordinate muon detector design and integration with the rest of the ILC detector.

University of California, Davis In the third year of the program, we expect to have fully analyzed the data. We will work on designing a full-scale readout system for a muon detector consisting of large scintillator planes. The lessons learned from the prototype system will be implemented in terms of design improvement, most notably in the time-synchronization area, and a version of the readout board with a large number of TriP chips will be developed. We expect that this work will be done by a graduate student at UCD. A cost estimate based on this new design will emerge and will be applicable to a realistic ILC muon detector.

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.

Three Year Budget – University of Notre Dame

ITEM	2005	2006	2007	Total
Other Professional	$30,000	$30,000	$30,000	$ 90,000
Graduate Student	$ 5,000	$ 5,000	$ 5,000	$ 15,000
Undergraduate Student				
Total Salaries and Wages	**$35,000**	**$35,000**	**$35,000**	**$105,000**
Fringe Benefits (20% of other prof.)	$ 6,000	$ 6,000	$ 6,000	$ 18,000
Total Salaries, Wages and Benefits	**$41,000**	**$41,000**	**$41,000**	**$123,000**
Equipment	$ 2,000	$ 6,000	$ 4,000	$ 12,000
Total Travel	$ 2,000	$ 2,000	$ 2,000	$ 6,000

Materials and Supplies				
Other Direct Costs				
Total Direct Costs	**$45,000**	**$49,000**	**$47,000**	**$141,000**
Indirect Costs (26% of MTDC)	$11,180	$11,180	$11,180	$ 33,540
Total Direct and Indirect Costs	**$56,180**	**$60,180**	**$58,180**	**$174,540**

Budget Justification: Wayne State University

Salary support is requested for 2 months per year for Research Engineer Alfredo Gutierrez in support of MAPMT instrumentation and testing. He has 9 years experience with computers and electronics for high energy physics experiments and has 2 years experience with MAPMT work for this project.

Support is requested for a graduate student for 1 academic term and during the summer, each year, to peform 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 4 MAPMTs and associated electronics components per year to instrument the prototype modules. Minor costs are also included for shipping of materials and for publications.

Three Year Budget – Wayne State University

ITEM	2005	2006	2007	Total
Other Professional	$ 8,670	$ 8,843	$ 9,020	$ 26,533
Graduate Student	$11,999	$12,239	$12,484	$ 36,722
Undergraduate Student				
Total Salaries and Wages	**$20,669**	**$21,082**	**$21,504**	**$ 63,255**
Fringe Benefits (26.4%)	$ 5,457	$ 5,566	$ 5,677	$ 16,700
Graduate Student Fee Remission	$ 3,871	$ 3,948	$ 4,027	$ 11,846
Total Salaries, Wages and Benefits	**$29,997**	**$30,596**	**$31,208**	**$ 91,801**
Equipment				
Total Travel	$ 6,500	$ 6,500	$ 6,500	$ 19,500
Materials and Supplies	$ 8,300	$ 8,300	$ 8,300	$ 24,900
Other Direct Costs				
Total Direct Costs	**$44,797**	**$45,396**	**$46,008**	**$136,201**
Indirect Costs (26% of MTDC)	$10,641	$10,776	$10,915	$ 32,332
Total Direct and Indirect Costs	**$55,438**	**$56,172**	**$56,923**	**$168,533**

Budget Justification: University of California, Davis.

Salary support is requested for a graduate student for two academic quarters and during the summer quarter, each year. During the first year, the student will work on the layout of the modified Minerva board and help with testing the prototypes. A total of 400 hours of undergraduate student support (@ $7.25/hour) is requested for each year.

Travel support is requested for three 1-week trips to Fermilab. In the first year this will be for installing the readout electronics at the muon test-stand. Additional support for travel to one domestic and one international Linear Collider workshops is requested for the P.I.

Equipment funds are requested to fabricate the modified Minerva boards. During the first year, we anticipate NRE costs of $3K and an additional $7.8K for producing 16 boards. In the second year, we will produce another 16 boards at a cost of $ 8K followed by 8 boards in the third year. The supplies budget of $2K/year is for miscellaneous electronics parts, software licenses, telephone and printing charges.

Three Year Budget – University of California, Davis.

ITEM	**2005**	**2006**	**2007**	**Total**
Other Professional				
Graduate Student	$16,785	$17,289	$17,808	$ 51,882
Undergraduate Student	$ 2,900	$ 2,900	$ 2,900	$ 8,700
Total Salaries and Wages	**$19,685**	**$20,189**	**$20,708**	**$ 60,582**
Fringe Benefits	$ 389	$ 397	$ 405	$ 1,191
Graduate Student Fee Remission	$ 6,166	$ 6,783	$ 7,461	$ 20,410
Total Salaries, Wages and Benefits	**$26,240**	**$27,369**	**$28,574**	**$ 82,183**
Equipment	$10,800	$ 8,000	$ 3,000	$ 21,800
Total Travel	$ 4,500	$ 4,725	$ 4,961	$ 14,186
Materials and Supplies	$ 2,000	$ 2,000	$ 2,000	$ 6,000
Other Direct Costs				
Total Direct Costs	**$43,540**	**$42,094**	**$38,535**	**$124,169**
Indirect Costs (26% of MTDC)	$ 6,909	$ 7,101	$ 7,299	$ 21,309
Total Direct and Indirect Costs	**$50,449**	**$49,195**	**$45,834**	**$145,478**