Development of GEM-based Forward Tracking Prototypes for the ILC

Classification (subsystem)

Tracking.

Personnel and Institution(s) requesting funding

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Project Overview

We propose a research and development effort for the International Linear Collider, based on our interest in forward tracking. We propose to study the need for additional tracking in the region beyond the TPC endplate (in the "Large Detector" scenario) and extending down to the masked region (approximately 100 mrad from the beamline.) We will evaluate the usefulness of an ionization chamber equipped with multiple gas electron multiplier (GEM) preamplifiers in this region; as such devices offer a fast, radiation-hard, low material profile tracking solution. Incorporating GEMs for forward tracking will also reduce the number of heterogeneous detector technologies in this region, since GEMs will likely be used to readout the TPC. This request is for renewal of current Department of Energy funding received through the Linear Collider Research and Development (LCRD) working group.

Previous uses of ionization-based tracking systems equipped with gas electron multiplier pre-amplification stages have found that such systems can provide 50 microns level resolution and radiation hardness up to 2Mrad. We intend to evaluate the system for use in the ILC by constructing a prototype to confirm the above observations and work to improve the system's response time as well as further test the radiation limits of a prototype detector using a high energy electron beam. We also propose a parallel program of simulations studies in the forward region, with particular emphasis on the tracking needs for luminosity measurements. We have made substantial progress in our first two years of activity in the LCRD working group. This progress is described in detail in the later section on Previous Research.

Forward Tracking Studies

Forward tracking will potentially be more important at the Linear Collider than at previous e+ e- colliders, as many interesting t-channel processes have differential cross sections peaked in the forward direction, including WW and WZ production. For SUSY searches, selectron pair production includes contributions from t-channel gaugino exchange. Other slepton production channels may be characterized by very forward, low p_T leptons due to small slepton-chargino mass splitting for some regions of the SUSY parameter space NEED REF! Detailed understanding of the Higgs boson can also potentially benefit from forward tracking. It will also be important to accurately measure differential luminosity cross-sections at the LC, with angular resolutions on the order of 0.1 mrad [1].

Several critical issues need to be addressed in determining the detector configuration best suited for forward tracking. These include background radiation levels and overall rates, triggering, timing resolution, and hit resolution when the forward detector is used in conjunction with other tracking elements.

We propose to address these issues through an integrated hardware and simulation effort. We will devote part of our Linear Collider effort to understanding the specific physics issues involved in forward tracking, and part to the development of a prototype tracking chamber which uses a gas electron multiplier technology for pre-amplification. Based on the observed performance of such devices, we feel this technology may be well-suited to the forward region

Gas Electron Multiplier-based Tracking

Several groups are currently exploring the fabrication of tracking detectors based on the use of gas electron multiplier (GEM) foils [3]. This includes the proposed Time Projection Chamber (TPC) which forms the central tracking component in the North American "Large Detector" concept as well as the detector outlined in the TELSA Technical Design Report [2]. Other GEM detector projects include the digital calorimeter option for the hadronic calorimeter. We propose to evaluate a forward tracking ionization chamber for the linear collider which uses a GEM as a preamplifier and will permit single particle tracking. We are working in close collaboration with others groups interested in applying GEMs to detectors for the ILC.

In the TESLA TDR, it is envisioned that there will be a layer of tracking between the TPC endplate and the endcap EM calorimeter (see Figure 1). This is called the Forward Chamber, or FCH, in the TESLA TDR and allows tracking segments in the central tracking volume to be extrapolated to the calorimeter, particularly in the region where there is reduced coverage or lever-arm for the TPC. As an application of GEM-based tracking, we are investigating the design of an FCH using GEM tracking chambers. (Other proposed technologies include straw tubes and silicon strips.)

A GEM is a perforated foil of insulating material approximately 50 microns thick and coated on both sides with a thin conductor approximately 5 microns thick. The holes have a radius on the order of 50 microns and are in a grid pattern in which the distance between adjacent holes is on the order of 150 microns. The photo-lithography based technology to construct this preamplifier was developed at CERN by Fabio Sauli and collaborators [4]. When used as a preamplifier in front of a micro-pattern device, like a multiwire proportional chamber, the signal is amplified 100 fold [5] and can operate in harsh radiation environments up to at least 2 Mrad [6]. Charge multiplication occurs when the electrons pass through the foil holes whose sides have had an electric potential difference applied to produce electric fields on the order of 40kV/cm. A typical GEM detector electric field is shown in Figure 1. With multiple

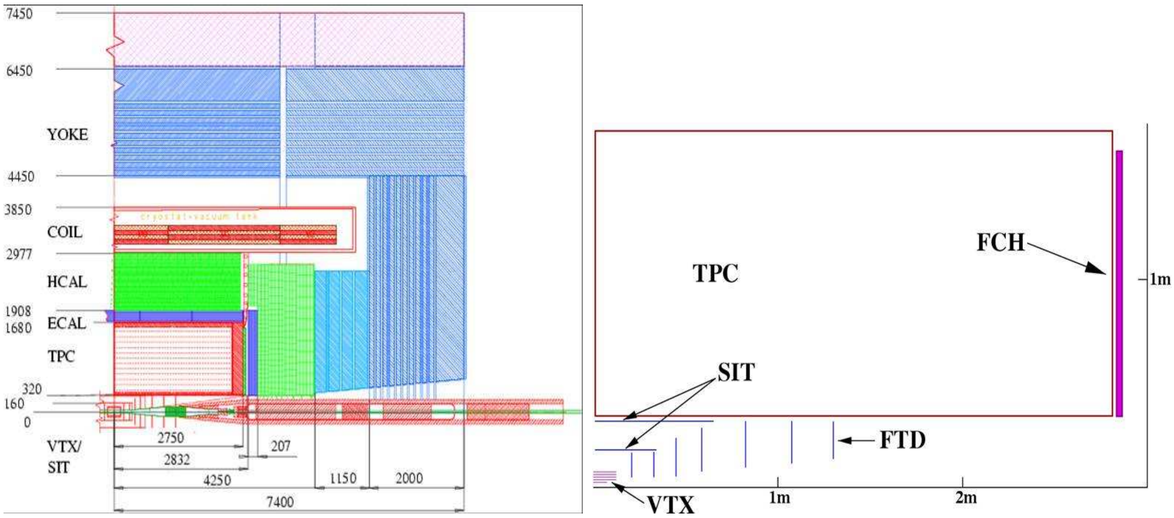

Figure 1: (left) A quarter view of the detector in the TESLA Technical Design Report. (right) The layout of the tracking, showing the FCH between the TPC and EM calorimeter. (Both figures taken from the TELSA TDR [2].).

GEMs serving as preamplifiers, the charge can be detected directly on a segmented printed circuit board due to the large gains which approach 10^6 [7].

As an application of GEM technology in subdetector systems at the linear collider, we will explore the use of GEM-based detectors in forward tracking. The GEM strategy offers the possibility of achieving the necessary spatial resolutions with a detector that is radiation-hard, high rate, and compact with a low material profile. This would fit the needs of an FCH, which has to fit within a slim gap between the TPC and EM calorimeter, at possibly a much lower cost than solid-state detector such silicon strips. Timing resolutions on the order of 14 ns have been measured with GEM detectors having a 3 mm gap. Research needs to be done to understand if faster timing can be achieved.

An evaluation of GEMs for use in the inner tracking system of HERA-B concluded that they are better suited for the harsh radiation environments of their experimental setup [8]. We would like to expand on their work to determine if a GEM-based forward tracking system is suitable for the ILC.

Detector Prototyping for the International Linear Collider

Outstanding issues to be addressed by this proposal involve a determination of the expected rates, lowest achievable scattering angle, desirable tracking resolution, readout rate and acceptable radiation length for use of this device. Triggering in the forward region, particularly with high backgrounds that are possible, may also be a significant technical challenge. We have begun work on a current monitor for the GEM detector, which we plan to develop into a differential current trigger. We propose to develop this current monitor trigger as part of our GEM detector prototyping activities, and to test the current monitor triggering scheme during an electron beam test of the GEM detector. (This differential current trigger may be useful for other groups exploring GEM-based detectors.)

In the progress report attached to this proposal, we detail our work to date in establishing a testing facility for the GEM based prototype tracking system. Briefly, an ionization chamber with two GEM preamplification stages and a 2-D charge collector has been procured from F.

Sauli's group at CERN during the first year of funding. Front end amplification, pulse shaping and 128 channel multiplexing electronics arrived during the first year of this work which were based on the HELIX128 chip developed by the Heidelberg ASIC laboratory in collaboration with a group from the MPI [8]. Students involved have been working on fabricating PC boards to integrate the HELIX chip onto the detector's charge collector, designing current monitors, installing driver signals for the HELIX chip and setting up a cosmic ray test stand. A data acquisition system is now in place with ADC and TDC readout electronics for 8 GEM channels. A second prototype detector, with three GEM preamplification stages, was constructed by Louisiana Tech students during the second year of this work and is currently operating in conjunction with our data acquisition. This prototype is shown in Figure 2

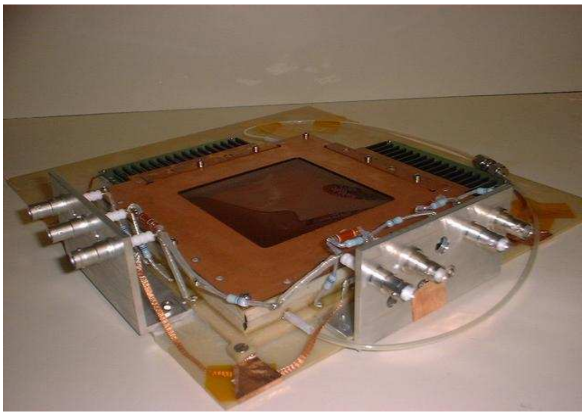

Figure 2: The second prototype 10cm x 10cm GEM tracking chamber, designed and developed by students at Louisiana Tech.

The challenge is to determine the optimal level of multiplexing which will reduce the probability of false hits to an acceptable level. In the case of the linear collider, a simulation will be used to determine what level of multiplexing will be needed. We can then investigate if it is desirable to adapt the HELIX128 to serve a similar function for the forward tracking device proposed here or use alternative methods of direct digitization which are currently being developed at CERN. At a future date, tests using a 1 GeV electron beam will also be done to evaluate readout performance at high rates as well as radiation hardness issues.

Broader Impact

Louisiana Tech University has a long tradition of involving underrepresented groups in research project. The last master's degree graduate was a woman, Jena Kraft, whose thesis was the evaluation of the gain and quantum efficiency properties of the GEM detector as a function of the gas pressure. We have a strong record of recruiting American students, including traditionally underrepresented minorities, into our physics program at both the undergraduate and graduate level.

An X-ray lab, developed for this project, has enhanced the infrastructure of the facilities at Louisiana Tech and will allow the research to expand into the area of medical imaging. We hope that the detector will have some impact on the current methods of medical imaging. A partnership has been created between the Biomedical Engineering department at Tech, the Biomedical Research Foundation of Shreveport, and the Center for Applied Physics studies to evaluate the usefulness of this device in the area of medical imaging.

Results of Prior Research

We report progress to date on our previous GEM-based detector development and forward simulations work. This work was carried out with support from a Department of Energy grant DE-FG02-99ER41117 ($505,000 over three years), covering the budget period 15 June, 2003 to 14 June, 2005, and LCRD-related supplements in 2003 ($37,490) and 2004 ($35,000).

We have made substantial progress in meeting the goals set out in last year's proposal, both in the area of GEM development and prototyping and in detector simulations. With the funding in hand, we have purchased Rohacell material for the detector prototype, a TTL-LVDS converter for our readout electronics, machine time for a prototype readout plane, and miscellaneous gas fittings and electronic components. We have designed and built two prototype GEM-based tracking chambers. We have initiated detailed studies of the electric field around the GEM holes, as well as simulations of angular resolution due to multiple scattering in the tracking chamber material. We have installed the simulation software for the full detector simulations needed to understand the detector parameters for the forward chambers in a TPC-based detector at the International Linear Collider.

We are funding two graduate students on this project, with money from the Department of Energy LCRD supplement and matching university funds. With travel funds provided in the LCRD supplement, we have participated in the the American Linear Collider Physics Group meetings in Stanford in January, 2004, and in Victoria in July, 2004. Recently we participated in the Workshop on Gaseous Detectors at the ILC, held at Ecole Polytechnique, Paliaseau, France on January 13-15, 2005. One of us (Sawyer) presented an overview of options for intermediate to forward instrumentation for a large TPC-based detector.

Detector Prototyping

A second prototype detector has been built by Louisiana Tech students which has an additional GEM preamplification stage compared to our first prototype but still has an 10cm x 10cm active area and a 2-D charge collector with a strip pitch of 400μm. A gas handling system, using 70% Ar and 30% CO_2, is in place along with regulators, connections lines, and bubbler. We are using a CAEN N470, 4 channels, 10 kV power supply to bias the GEM detector and X-ray source. A trigger circuit has been installed on the second prototype detector which is being using to trigger the DAQ readout of up to 8 detector channels.

Another student has fabricated PC boards using our Protomat machine to short out the GEM readout lines in order to facilitate the use of our limited number of readout channels currently available. The student is also designing a PC board ("pitch adapter") to carry the GEM trace lines to the HELIX readout boards which we have recently procured. These readout boards were developed by the Heidelberg ASIC laboratory in collaboration with a group from Max Planck Institute to utilize a highly integrated and radiation hard readout chip called the "HELIX 128 " which can read out 128 anode strips at 40 MHz and store the information for last 8 events in a pipeline citeHELIX. The GEM connectors for this board have just arrived from Felco Electronics. The next step will involve using a wire bonding machining to connect the Helix input pads to the pitch adapter output lines.

Another student is working to provide the low voltage differential signals (LVDS) to control the Helix chip. The initial attempt by the student was to use our in-house function generators to create the LVDS signals. This was abandoned due to the high noise levels (150 mV) on the function generator output. An LVDS signal converter chip has been purchase to output 4 LVDS pulses from a single TTL input pulse. A data acquisition system, based on the CODA system developed at Jefferson National Laboratory, is now in place. Currently we are reading

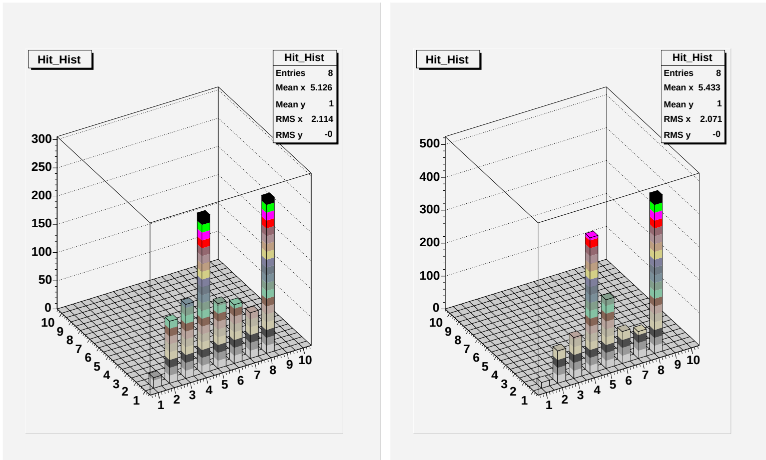

Figure 3: A sample GEM detector hit. The left figure shows a single hit on detector channel 4 while rht right most figure illustrates a multiple hit on channels 4 and 5. Channel 8 represents the measured charge of the trigger signal. Channel 1 & 7 are pedestal channels.

a LeCroy 1182 8-channel ADC. DAQ files are being written to disk and software has been written to convert the RAW data files to ROOT ntuples for analysis. The next step is install the Lecroy TDC into the readout list in order to perform timing studies.

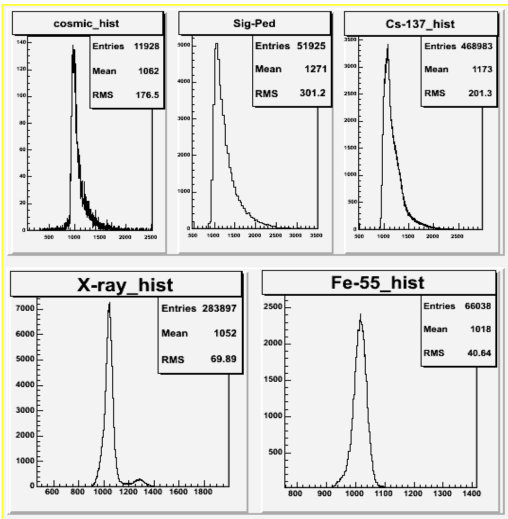

Figure 4: A sample of several different ionization sources measured by the second prototype detector

A charge collector has been designed using Autodesk. The structural dimensions may be altered by simply editing an excel spreadsheet which contains the relevant parameters. A prototype charge collector board has been received from CERN that has 15 μm thick copper traces layed down on 1.7 mm thick G-10. The next charge collector boards will have 5 μm copper traces layed down on 120 μm thick G-10. Because of oxidation problems with the first prototype detector, the charge collectors are now being coated with 2 μm of Nickel and 0.1 μm of Gold. Wire bonds between the output connector and the charge lines have also been eliminated to improve detector robustness.

A pulsed X-ray tube is being used to perform detailed position resolution as well as response time studies on the completed prototype detector. The CAEN N470 power supply is used in conjunction with a newly acquired PVX-4140 high voltage pulse generator from Directed Energy, Inc. to pulse the nanotube based X-ray source. The pulse generator can apply up to 3500 kV within 25 ns and has a tight pulse width of 60 ns. When collimated, this pulsed X-ray source will be used to perform position and timing measurements of the detector.

In collaboration with the University of Texas at Arlington and the University of Victoria, we will be testing new 30cm x 30cm GEM foils produced by the 3M corporation. A design for a tracking chamber incorporating these larger GEM foils is being developed.

Simulation Studies

We have begun detector simulation studies on two fronts: detailed studies of GEM chamber simulations in order to better understand pulse shape, ionization, and drift times; and GEANT4-based studies of the forward tracking needs of the proposed ILC detectors configurations, with a particular interest in forward tracking needs.

ANSYS has been used to calculate the electric field of a GEM foil. A 2-D model was constructed which had the same characteristics as other published models. A 3-D model is now being developed which reduces the perforated hole pattern into a fundamental pattern based on 1/4 of 2 adjacent holes. The electric field map for the entire GEM foil may be generated from this. The goal will be to generate an electric field map for use in a program which simulates the gas ionization process. The program GARFIELD[10] is a popular simulation program for drift chambers which we may borrow from for our needs. The key ingredients are the function HEED [11], used to calculate energy loss due to ionization in the drift chamber gas, and MagBoltz [12], used to track electrons in a gas. Detailed figures from these field studies were included in our earlier progress report.

A GEANT3 [13] based study of the prototype GEM-based tracking chamber has been performed. The effect of multiple scattering on a 1 GeV electron which traverses the detector was investigated. The angular resolution is degraded by about 15% when a triple GEM ionization chamber is used to detect electrons emerging at 9 ± 2 degrees with respect to the beamline. The final step in detector simulation will be to incorporate the proposed detector system into the full GEANT4-based Linear Collider Detector simulation, in order to study the performance of the detector in the forward region of the Large Detector configuration. Currently, we are still in the process of installing GEANT4 and the LCDROOT packages (along with other required software packages) on our Linux cluster. During the summer, 2004, we stationed one of our graduate students with the simulations group at Northern Illinois University, in order for him to learn the GEANT4 and LCD4 software. He is now in charge of installing and maintaining that software on our cluster. However, as the conceptual design process has taken shape over the last several months, we now believe that we can best proceed by modifying the existing Mokka simulation framework, which was used for the TESLA TDR studies. We are currently installing Mokka, and plan to have results for the International Linear Collider in Stanford, March 18-20, 2005.

References

[1] "Linear Collider Physics REsource Book for Snowmass 2001", American Linear Collider Working Group. For more recent SUSY studies in the forward region, see Phillippe Bambade's talk at the Machine-Detector Interface Workshop, available at http://www-conf.slac.stanford.edu/mdi/default.htm.

[2] The TESLA Techinical Design Report, available at http://tesla.desy.de/new_pages/TDR_CD/start.html.

[3] For a general discussion of GEM detector technology, see the papers listed on http://www.jlab.org/g̃en/detectors/literature_gem.html.

[4] F. Sauli, Nucl. Instr. and Meth., A 386 (1997) 531.

[5] W. Beaumont, et. al. , Nucl. Instum. and Meth. A 419 (1998) 394.

[6] B. Schmidt, Nucl. Instrum. and Meth. A 419 (1998) 230.

[7] A. Bressan et. al., Nucl. Instrum. and Meth A 425 (1999) 262.

[8] Y. Bagaturia et. al., hep-ex/0204011.

[9] For a full description, see "Helix128-x User Manual", ASIC Labor Heidelberg preprint HD-ASIC-33-0697. (V2.1, 3.2.1999)

[10] For a description see http://consult.cern.ch/writeup/garfield/

[11] For a description see http://consult.cern.ch/writeup/heed/

[12] For a description see http://consult.cern.ch/writeup/magboltz/

[13] F. Carminati, et al, The GEANT Users Guide, CERN Program Library W5013, 1991.

Facilities, Equipment and Other Resources

This research project represents collaboration between the Institute for Micromanufacturing and the Center for Applied Physics Studies at Louisiana Tech University. The Institute for Micromanufacturing has the facilities to fabricate the ionization chambers, assemble the components in clean rooms, and wire bond the readout electronics to the ionization chamber. To shorten development time, GEM foils will be purchased. The Center for Applied Physics Studies contains the high energy and medium energy physics groups who will be developing the GEM detectors. The collective experiences of the Center for Applied Physics Studies members will ensure the development a GEM-based forward tracking prototype and detailed studies of the tracking needs in the forward region..

The principal investigators (Sawyer, Greenwood) are members of the high energy physics group at Louisiana Tech, are members of the D0 experiment at Fermilab, and have extensive experience in detector development and simulations. The Louisiana Tech group built and installed portions of the Intercryostat Detector for the D0 upgrade. Dr. Sawyer has worked on the ALEPH, D0, SDC, and ATLAS experiments, while Dr. Greenwood has built a number of neutrino detectors and is currently involved in Run IIb upgrades to the D0 Silicon Tracker.

Our collaborator, Tony Forest, is a member of Louisiana Tech's medium energy group, with experiments at Jefferson Lab. He is developing GEM-based trackers for the proposed Qweak experiment at JLAB. His experience with tracking in that detector system will be used in developing the forward tracking prototype. In addition, other members of the medium energy group are collaborating on studies of GEM-based tracking applications, and students from both the high energy and medium energy groups are collaborating in our detector development lab.

FY2005 Project Activities and Deliverables

In year one of our renewal request, we will build a prototype GEM-based tracking detector using the new 30cm X 30cm GEM foils from 3M. We will carefully test this chamber's performance compared to the 10cm X 10cm currently being tested, which foils manufactured at CERN. We will use our new X-ray test facility, as well as source and cosmic ray testing. The X-ray lab is a new addition to CAPS, is based on carbon nanotube technology to facilitate pulsing and is capable of delivery 1 kHz of 8 and 20 keV photons. The goals of these tests will be to establish the operational limits of the proto-type device.

We will continue our simulation studies of forward tracking at the LC. We will use the Mokka front-end to GEANT4 to perform detailed studies of the improvement to tracking with a Forward Chamber (FCH) between the TPC endplate and the EM calorimeter. We will begin studies of different detector readout configurations and begin the process of optimizing the detector design for the GEM tracker FCH.

FY2006 Project Activities and Deliverables

In year two, we will perform beam tests of a prototype tracker module. We will plan for the installation of the device at Jefferson Lab which is capable of delivering up to 100 microamp of 6 GeV electrons to a target. Our plan is to install the prototype in Hall C at Jefferson Lab. This would be preferably in conjunction with a running experimental setup but we could conceivably setup a standalone beam test. The goal of these tests will be to evaluate the operational rate limits of the detector readout system and determine the impact of radiation damage.

In year two, we will finalize a design for the FCH, based on our simulation studies. This should coincide with the timetable for detector conceptual design to be formulated. We will contribute to the conceptual Design of a TPC-based detector for the International Linear Collider, with emphasis on the FCH and tracking in the intermediate to forward regions.

FY2007 Project Activities and Deliverables

In year three, we will analyze the results of the beam studies. In conjunction with the results of simulation studies, we will then be able to propose a full forward tracking detector for the LC detector, which will hopefully be in the Technical Design stage by this point (year 2006-2007). We will use the pulsed X-ray facility at Louisiana Tech to investigate the effect of ionization chamber and GEM preamplifier wall thicknesses on pulse risetime in the GEM.

Budget justification: Louisiana Tech University

Our budget request for year one is based on the purchase of an additional 4 GEM foils from 3M ($2600), machining time for the prototype components ($700), construction cost for additional readout plane construction ($1000), and costs of prototyping the readout electronics ($1000). We will also need clean room time for GEM detector assembly, for which we request 20 hours at$60/hour ($1200). We request continued support for one Ph.D. student ($14,000). We request modest travel funds ($5,000) to cover the additional costs of attending ILC meetings, which are beyond the scope of current base Dept. of Energy grant.

For year two, our budget request includes expenses for beam tests as well as continued simulation studies. For the beam tests, we will need power isolation transformer ($500), cabling ($900), power supply for the HELIX128 readout ($100), gaslines and bottles ($200). We will need at least 4 trips to the beam line, estimated at $1,500 per trip based on past experience from the medium energy group. We request continued support for one Ph.D. student

($14,000). Because of the travel request for beam tests, we reduce our request for travel to ILC meetings to $2000, and will attempt to secure additional travel funds to make up the difference.

For year three, we request funds for replacement GEM foils ($900), machining time for test chamber walls ($500) and supplies. We request continued support for one Ph.D. student ($14,000). We request travel funds of $7,000 to cover the predicted increased number of trips needed to collaborate on the Technical Design Report for the TPC-based detector.

Three-year budget, in then-year K$

Institution: Louisiana Tech University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	0	0
Graduate Students	$ 14,000	$ 14,000	$ 14,000	$ 42,000
Undergraduate Students	0	0	0	0
Total Salaries and Wages	$ 14,000	$ 14,000	$ 14,000	$ 42,000
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	$ 14,000	$ 14,000	$ 14,000	$ 42,000
Equipment	0	$ 600	0	$ 600
Travel	$ 5,000	$ 8,000	$ 7,000	$ 19,000
Materials and Supplies	$ 6,500	$ 1,100	$ 1,400	$ 9,000
Other direct costs	0	0	0	0
Total direct costs	$ 25,500	$ 23,700	$ 22,400	$ 71,600
Indirect costs(1)	$ 6,720	$ 6,720	$ 6,720	$ 20,160
Total direct and indirect costs	$ 32,220	$ 30,420	$ 29,120	$ 91,760

(1) Includes 48% of salary and wages only