Development of Forward Tracking and GEM-based Tracking Prototypes for the ILC

Classification (subsystem)
Tracking

Personnel and Institution(s) requesting funding
Lee Sawyer
Z.D. Greenwood
Center for Applied Physics Studies
Louisiana Tech University
Ruston, LA 71272 (318) 257-4053

Rick Van Kooten (as of FY2006)
Physics Department
Indiana University
Swain West 117
Bloomington, IN 47405
(812) 855-2650

Collaborators
Tony Forest
Center for Applied Physics Studies
Louisiana Tech University
Ruston, LA 71272

Project Leader
Lee Sawyer
sawyer@phys.latech.edu
(318) 257-4053

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” Concept, or LDC) and extending down to the forward-most edge of the tracking acceptance 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 preamplification stages have found that such systems can provide 60 microns level resolution and radiation hardness up to 2 Mrad. 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 luminosity measurements, implications of forward tracking on particle flow algorithms, and the interplay of design choices of the TPC on overall detector performance in the forward region with supplemental tracking. We have made substantial progress in our first three 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, dominant background channels to many new physics and intermediate mass Higgs decays. 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. 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 “Large Detector Concept” (LDC), an outgrowth of the previous North American “LD” design as well as the detector outlined in the TESLA 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 was envisioned that there will be a layer of tracking between the TPC endplate and the endcap EM calorimeter (see Figure 1). This was 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, and hence fewer space point hits, or lever-arm for the TPC. In the latest discussion of the LDC this detector has been called the ETD, or Endcap Tracking Detector. We retain the term FCH in this report as it more familiar at the moment. 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.) Both Sawyer and van Kooten are part of the editorial team in charge of Conceptual Design Report for the LDC, and with Aurora Savoy-Navarro of LPNHE-Paris and Klaus Monig of DESY are responsible for studies of the other tracking elements augmenting the TPC.

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 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 sub-detector 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 developed a current monitor for the GEM detector, which we plan to use as part of 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 was 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.

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

Figure 2: The second prototype 10 cm x 10 cm GEM tracking chamber, designed and developed by students at Louisiana Tech.
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 under-represented groups in research project. A previous 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 under-represented 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.

Indiana University has been a QuarkNet center from the very first year of its inception in 1999 with the participation of 150 high school students and 10 high school teachers. They have been involved in learning the concepts of particle physics and participating in hands-on construction activities such as cosmic ray telescopes operating at six Indiana high schools. The particle physics group has also had excellent success in attracting and mentoring undergraduate students as part of a Science, Technology, and Research Scholars program partnering outstanding students with faculty through all their four years of their stay at Indiana University.

**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). In 2005, we were awarded $27,000 as a sub-contract through the combined International Linear Collider University-based Linear Collider Detector program, funded jointly through the DoE and the NSF.

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 reported 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
we have participated in 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, Palaiseau, 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. Members of both Louisiana Tech and Indiana’s ILC groups participated in the Snowmass Linear Collider workshop, and one of us (Sawyer) attended the ECFA Linear Collider Workshop and follow-up LDC meeting in Vienna in November, 2005.

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 400um. A gas handling system, using 70% Ar and 30% CO2, 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 used to trigger the DAQ readout of up to 16 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 [8]. The GEM connectors for this board were purchased from Felco Electronics.

We evaluated the HELIX-128 readout board for the GEM detector. A single board computer was programmed to download board parameters through a serial interface. Unfortunately, the HELIX board failed to maintain or reproduce the parameters programmed through the serial interface. We observed that he HELIX board preamplification stage changed with time. An alternative readout scheme, currently being used at Jefferson Lab on a similar detector, is being adapted for use until the HELIX board problem is understood. A preamplifier card from the Jefferson Lab electronics has been installed on the Louisiana Tech GEM detector prototype. The response time of the preamp card is sufficient for our application. The preamp card will be altered to include additional amplification and then used in conjunction with the front end electronics from Jefferson Lab for a complete readout system. A faster readout scheme is still sought due to the slow (microsec) front end electronics response times.

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 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.

A charge collector has been designed using Autodesk for the 10 cm x 10 cm prototypes, and
Figure 3: A sample GEM detector hit. The top trace shows the Jefferson Lab-built preamp signal, while the bottom trace shows the signal read directly from the third GEM foil.

Figure 4: A sample of several different ionization sources measured by the second prototype detector.
constructed for us at CERN. 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 \( \mu \)m thick copper traces laid down on 1.7 mm thick G-10. The next charge collector boards will have 5 \( \mu \)m copper traces laid down on 120 \( \mu \)m thick G-10. Because of oxidation problems with the first prototype detector, the charge collectors are now being coated with 2 \( \mu \)m of Nickel and 0.1 \( \mu \)m 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.

One of our students has been designing and machining the ionization chamber and a high voltage distribution board for the GEM foils within the gas chamber. Ionization chamber frames for the second 10 cm \( \times \) 10 cm active area prototype have been designed and machined from FR4 in the Louisiana Tech machine shop. Based on that experience, the design is being ported to a programmable milling machine which has become available in the Louisiana Tech machine shop. Machining time for either a 10 cm \( \times \) 10 cm or a 30 cm \( \times \) 30 cm size ionization chamber will be drastically reduced after this infrastructure is in place. A substantial effort has been taken to redesign the HV distribution board used in the original GEM prototype detector. The previous HV network contained too many sharp edges which would be responsible for low noise spark discharges. The new HV network is contained on a PC board most of which is within the gas chamber. This should substantially reduce the leakage current. The 30 cm \( \times \) 30 cm GEM foils which have recently arrived from 3M will be framed and HV tested for use.

In collaboration with the University of Texas at Arlington and the University of Victoria, we will be testing new 30cm \( \times \) 30cm GEM foils produced by the 3M corporation. A design for a tracking chamber incorporating these larger GEM foils is being developed. The first of the 30 cm \( \times \) 30 cm foils were received as this progress report was being written.

**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 and its contribution to particle flow algorithms in the endcap regions.

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
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 $9 \pm 2$ 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 is being used for detailed studies for the LDC conceptual design report.

While the Mokka-based simulations are getting underway, we have also obtained preliminary results using the SGV [14] fast simulation framework. These results were shown at the Snowmass Linear Collider workshop in August, 2005; and at the LDC meeting in Vienna in November, 2005. We have used SGV to study the dependence of the momentum resolution on the number of FCH hits and there relative spacing between the TPC endplate and the endcap calorimeter. The main result of these studies has been that some number of precision hits are needed in this region, but the gain in precision between a few evenly spaced hits and several hits is marginal at this level of simulation. Since SGV has limited ability to simulate the effect of material (bremsstrahlung only) the effect of the FCH on particle flow will await the more detailed Mokka studies.
Figure 6: Momentum resolution vs momentum for $\theta = 8$ deg (left) and vs theta for $p = 100$ GeV/c electrons (right). In each case the green data points represent no FCH hits, the yellow data points 2 layers of precision hits, the blue point 10 layers.

References


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.

Co-PI Van Kooten, joining the effort this year, is a member of the particle physics group at Indiana, is currently a member of the D0 Collaboration at Fermilab, and has a great deal of experience in the simulation, construction, and commissioning of tracking systems in the D0 (built and installed parts of the scintillating fiber tracker), OPAL, and Mark II detectors. He was co-convenor of the American Higgs Physics Working Group for five years, and his physics research has included new particle searches, including searches for supersymmetric particles.

FY2005 Project Activities and Deliverables

In year one of our renewal request, we will build a prototype GEM-based tracking detector using the new 30 cm × 30 cm GEM foils from 3M. We will carefully test this chamber’s performance compared to the 10 cm × 10 cm 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.

During the first year, our new collaborator, van Kooten, will begin applying the Mokka-based simulations to studies of particle flow and overall detector performance in the forward
direction. Together we will contribute to the writing and editing of the LDC conceptual design report.

**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, and its impact on other subdetectors.

**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

As a result of the LCDRD review process, we have been granted funding for Year One of $27,000, with the assumption of flat (same in then-year dollars) funding in Years Two and Three for budgeting purposes. Our budget request for materials and supplies for Year One will be based on the purchase of readout planes for a 30 cm x 30 cm prototype chamber, to be ordered from CERN ($3,000), machining time for the prototype components ($500), and costs of prototyping the readout electronics ($1100). We will also need clean room time for GEM detector assembly, for which we request 15 hours at $60/hour ($900). Because of the budget reduction, we will not be able to buy additional GEM foils, but will have to rely on those purchased with the last year’s funding through our DoE supplement.

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), power supply for the HELIX128 readout ($100), gaslines, bottles and cabling ($900); bringing the total equipment, material, and supplies budgets to $1,500. (This is lower than originally estimated, and we will begin seeking additional support immediately to cover cabling and gas costs.) 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 at Louisiana Tech. In order to not impact the amount of time that can be spent at a test beam in Year Two, we increase the total travel budget to $7,000. We request continued support for one Ph.D. student ($12,500).

For Year Three, we request funds for replacement GEM foils ($1000), machining time for test chamber walls ($500) and supplies. We request continued support for one Ph.D. student ($12,500). 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 Large Gaseous Detector. This budget is essentially unchanged from the original request, with the exception of the reduced graduate student stipend and associated indirect costs reduction.

In all years, indirect (F&A) costs are computed at 48% of total salaries and wages only. Three-year budget, in then-year K$

### Three-year budget, in then-year $

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(1) Includes 48% of salary and wages only

**Budget justification:** Indiana University

The budget request for year two and three is to cover hourly salaries of undergraduate students to work on simulations of the forward tracker. An amount of $10,250 each year would cover summer salary of one full-time student plus one or more students during the academic year. We plan at least two ILC-related trips, one to one ILC conference ($1,000), plus trips to simulation workshops ($1,000) in each year. In year three, we add a travel request of $2,000 to cover the predicted increased number of trips needed to collaborate on the Technical Design Report for the TPC-based detector. We would also contribute towards beam tests in years two and three ($1,500 each year).

### Three-year budget, in then-year $

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<td>$10,250</td>
<td>$10,250</td>
<td>20,500</td>
</tr>
<tr>
<td>Fringe Benefits</td>
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</tr>
<tr>
<td>Total Salaries, Wages and Fringe Benefits</td>
<td>–</td>
<td>$10,250</td>
<td>$10,250</td>
<td>20,500</td>
</tr>
<tr>
<td>Equipment</td>
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<tr>
<td>Travel</td>
<td>–</td>
<td>$3,500</td>
<td>$5,500</td>
<td>$9,000</td>
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<tr>
<td>Materials and Supplies</td>
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<tr>
<td>Other direct costs</td>
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<tr>
<td>Total direct costs</td>
<td>–</td>
<td>$13,750</td>
<td>$15,750</td>
<td>$29,500</td>
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<tr>
<td>Indirect costs</td>
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<td>0</td>
</tr>
<tr>
<td>Total direct and indirect costs</td>
<td>–</td>
<td>$13,750</td>
<td>$15,750</td>
<td>$29,500</td>
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