University-based Detector R&D for a Linear Collider
Appendix

In this Appendix, the full project descriptions are given for each of the UCLC projects. The numbering scheme is the same as in the proposal's Project Description.

Contents

2 Machine-Detector Interface

2.1 A Demonstration of the Electronic and Mechanical Stability of a BPM-Based Energy Spectrometer for an Electron-Positron Linear Collider

Personnel and Institution(s) requesting funding

Michael D. Hildreth, University of Notre Dame

Collaborators

Yury Kolomensky, Lawrence Berkeley National Laboratory and University of California, Berkeley

Joe Frisch, Peter Tenenbaum, Stanford Linear Accelerator Center

Project Leader

M. Hildreth
mikeh@undhep.hep.nd.edu
(574) 631-6458

Changes Since Preliminary Project Description

The budget was reduced to reflect current accounting of fringe benefits on graduate students and to more properly account for the time spent by professionals on the project.

Project Overview

Much of the physics of the future e^+e^- Linear Collider will depend on a precise measurement of the center-of-mass energy (E_{CM}), the differential dependence of luminosity on energy ($\mathrm{d}\mathcal{L}/\mathrm{d}E$), and the relationship between these two quantities and the energy of a single beam (E_{beam}). Studies estimating the precision of future measurements of the top mass[1] and the higgs mass[2] indicate that a measurement of the absolute beam energy scale of 50 MeV for a 250 GeV beam ($\delta E_{\mathrm{beam}}/E_{\mathrm{beam}} \sim 1{-}2\times10^{-4}$) will be necessary to avoid dominating the statistical and systematic errors on these masses. If precision electroweak measurements become necessary, the requirements on the beam energy measurement are even more stringent. Studies of a scan of the WW pair production threshold[3] have shown that an experimental error of 6 MeV may be possible, implying a needed precision of $\delta E_{\mathrm{beam}}/E_{\mathrm{beam}} \sim 3\times10^{-5}$ (and likely an alteration in accelerator parameters to control $\mathrm{d}\mathcal{L}/\mathrm{d}E$). Provisions must be made in the overall accelerator design to provide adequate beamline space for the devices which will provide these energy measurements. Moving accelerator components well after construction in order to provide additional space for energy measurement instrumentation is likely to be both extremely disruptive and extremely expensive. We are in a situation, however, where no direct energy measurement technique except resonant depolarization (RDP)[4] has provided an energy determination of sufficient precision. Since RDP will not work in a single-pass collider, spectrometer techniques must be developed which meet the specifications demanded by physics measurements.

Previous experimental requirements on precision energy measurements at electron-based accelerators have led to the development of several techniques. At Jefferson Lab, wire scanners, etc.[5] have been used to provide a precision of $\delta E_{\mathrm{beam}}/E_{\mathrm{beam}} \sim 1\times10^{-4}$ at beam energies of about 4 GeV. At higher energies, dedicated magnetic spectrometers have been constructed. At the SLC, the WISRD (Wire Imaging Synchrotron Radiation Detector)[6] was used to measure the distance between two synchrotron stripes created by vertical bend magnets which surrounded a precisely-measured dipole that provided a horizontal bend proportional to the beam energy ($\sim$ 45 GeV). This device reached a precision of $\delta E_{\text{beam}}/E_{\text{beam}} \sim 2\times10^{-4}$, where the limiting systematic errors were due to the relative alignment between the three dipole magnets and backround issues associated with measuring the precise centroids of the synchrotron stripes. At LEP2, a magnetic spectrometer was incorporated into the LEP ring[7]. A precise map of the magnetic field at a series of excitations allowed a comparison of the nearly-constant bend angle across a range of LEP beam energies. Since a precise calibration using RDP at the Z^0 pole was possible, the spectrometer provided a relative energy measurement between this lower point and and physics energies ($\sim$ 100 GeV). In this case, standard LEP Beam Position Monitors (BPMs) fitted with custom electronics were used to provide the angle measurement. This spectrometer has provided an energy determination at LEP2 energies of $\delta E_{\text{beam}}/E_{\text{beam}} \sim 2\times10^{-4}$, where the dominant errors have come from the stability of the BPM electronics.

As can be seen from the above results, LC physics may require between a factor of 5 and 10 more precise energy determination than has been achieved with existing techniques. Bridging this gap is an essentially-technical challenge, where clever engineering solutions to the problems of nanometer-scale stability and resolution will be necessary. We are currently interested in developing a prototype support and position-monitoring system for the "magnetic spectrometer" option for Energy measurement, and, coupled with RF-BPM development at LBL, a protype BPM station which can demonstrate the required accuracy and stability in an electron beam test. The end goal of the proposal is the design of a magnetic-spectrometer-based Energy Measurement system for the LC which can reach the desired precision. The "magnetic spectrometer" option is chosen as the focus primarily because it may be the only technique capable of achieving this goal.

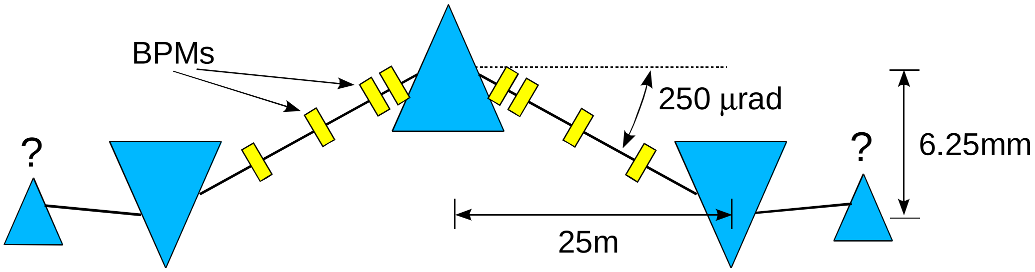

Figure 1: A schematic outline of an accelerator dipole chicane which could accomodate a BPM-based magnetic spectrometer at a future linear collider.

As summarized in Figure 1, a magnetic spectrometer at the LC will consist of a chicane of dipoles, with one central well-measured magnet. To avoid hysteresis effects, this central dipole should be super-conducting rather than a typical iron dipole. In order to make an absolute, stand-alone energy measurement, the main dipole will need to be turned "off", in the situation shown at the top of Figure 2. Once the BPMs measure a straight line, the dipole can be re-energized, and the deflection angle relative to the initial straight line can be measured, determining the energy. In order to do this: the BPM response/gain/calibration must be stable over the time it takes to move the BPMs on the beam center; the position of each of the BPMs relative to the inertial straight line must be known with sufficient accuracy and stability; and the BPMs must be able to be moved repeatedly and accurately over length scales of order 1cm with a precision of tens of nanometers. This proposal seeks to demonstrate the feasibility of each of these conditions.

The exact details of the accelerator optics around the spectrometer have yet to be fleshed out (see FY2003 deliverables), and in fact will ultimately depend on the achievable stability and resolution. A suitable chicane can be designed which will allow the straight-ahead and deflected beams to pass through to the rest of the accelerator with an acceptable emittance growth while providing a sufficient lever-arm to match the expected BPM position/stability resolution. Given current superconducting magnet technology and the resolution achieved by RF BPMs, drift lengths of order 20 meters with a 500 mrad bend are approximately correct for this system. It is clear that this measurement will not be performed continously; periodic measurements on a week-by-week timescale should be adequate.

Prototyping a BPM-based Energy Spectrometer breaks down into three natural stages:

1. establishment of a reference "straight line" optical system to serve as the reference line for the energy measurement; demonstration of its stability and sensitivity to motion
2. establishment of a means to measure distances perpendicular to this straight line reference in order to determine relative transverse motion of accelerator compononents; demonstration of the sensitivity and stability
3. addition of a BPM triplet or quadruplet to measure beam position, resolution, and stability of position. This last part requires a beam test.

Establishment of an "straight" line is most easily achieved optically in this case with a laser interferometer, which will be set up under vacuum to minimize thermal effects. Monitoring of the relative positions of the BPMs and the optical elements themselves can be achieved using the same techniques that have been developed for the stabilization of the LC Final Focus quadrupoles at SLAC and at the University of British Columbia[8]. We hope to benefit by borrowing many of their techniques and advances. Sensitivity tests at this stage require piezo movers of known calibration, and perhaps a capacitive position encoder.

For the geometry shown in Figures 1 and 2, the required BPM resolution and stability of measurement varies from 15 nm very close to the dipole to 190 nm at a distance of 25 meters. Since RF-BPMs with a resolution of 25 nm[9] have been used at the Final Focus Test Beam at SLAC, the necessary performance in terms of pure resolution has nearly been achieved for the full range of possible BPM positions. Stability over the measurement time, however, has yet to be demonstrated. Development at LBL/Berkeley will focus on these issues, as they will provide the RF BPM componenets which complement the mechanical systems outlined here.

A crucial item for this project is the BPM movers. Advances in technology for nano-manufacturing have come along at an opportune time in order to drastically reduce the cost (and increase the performance) of nano-movers. Several firms have developed or are developing this technolgy. At this stage, an SBIR project with one of the leading developers may be a way of gaining access to this technology in an economical manner. Spectacular performance, such as sub-nm positioning accuracy over multiple *centimeter* travel distance is now available almost "off-the-shelf" at very reasonable cost. It is expected that the mover supports and BPM stands will be based on SLAC magnet stand designs that have successfully demonstrated sub-micron stability. SLAC designers will act as consultants on the support stand design and fabrication.

Once the mechanical and electrical systems have matured, a test of position resolution and stability in a real beamline is essential for the success of the spectrometer. Many beam-induced effects are possible (and were experienced in building the LEP Spectrometer), such that significant beam test time will be necessary in order to iterate on the electronic or mechanical systems if needed. Only then can one arrive at a final design with sufficient performance. As well as contributing invaluable ideas and insights throughout the process, our SLAC collaborators will provide logistical support and coordination for the final stage of the project when beam tests occur.

FY2004 Project Activities and Deliverables

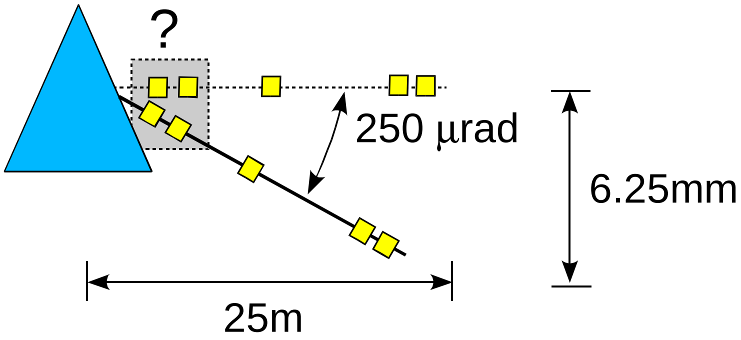

Figure 2: A diagram showing the two cases of: straight-ahead linear trajectory measurement to establish zero deflection; and the motion of the BPMs necessary to measure a deflection of 250μrad. The "?" indicates that it may be possible to design a system with sufficient accuracy that the closest BPM to the dipole can remain stationary and still have sufficient precision on the position measurement to serve as a BPM "anchor" for the measurement.

The first year of the project will include the establishment of the linear optical reference using interferometric techniques and measurements of its sensitivity. The transverse monitoring system will also be set up. Development of appropriate nano-movers for the BPM positioning will begin. In parallel, an investigation of the potential locations of such a device in the accelerator lattice will be explored. The first deliverable is a measurement of the power spectrum of random motion transverse to a 5m length of optical anchor. The second deliverable is an optics deck for the NLC and Tesla designs including the energy spectrometer.

FY2005 Project Activities and Deliverables

The second year of the project will include measurements of the stability of a prototype BPM stand transverse to the optical straight line. Vertical and angular stability will also be explored. The second-year deliverables are a mechanical design of a BPM stand with sufficient (10nm at low frequencies) transverse stability to carry the RF-BPMs necessary for the beam test and a design and/or a prototype for the BPM nanomover.

FY2006 Project Activities and Deliverables

The third year will see the completion of the BPM nanomover and the assembly of a BPM test stand sufficient for a beam test of the stability and resolution of the system. Deliverables for the third year will include a measurement of the resolution and stability of the BPM pickup determined from a triplet or quadruplet of RF-BPMs placed in an electron beam. The systematics of these measurements (i.e., dependence on position within the BPM, beam current, beam tails, etc.) will also be pursued. The results of these tests will determine the required footprint of a magnetic spectrometer in the LC design.

Budget justification

The first year's experiments involve setting up the optical interferometer system and making some simple measurements. This will be accomplished by staff members (not included here) with the help of an undergraduate and a half-time graduate student. Sufficient equipment and supply funds are included in order to purchase the interferometer, a vacuum system in which to run it, and piezo movers for testing. Travel funds sufficient for visiting collaborating institutions are included throughout.

The second year will involve mechanical design and fabrication of a BPM support structure. Costs for engineering (1/3 FTE) and fabrication are included. Manpower for mounting this effort will come from an undergraduate student and a full-time graduate student as well as staff (not included).

In the third year, the aid of a half-time postdoc will be enlisted to help carry out the beam test. The nano-mover purchase dominates the equipment costs for this year. Travel costs will increase in order to setup and perform the beam test of the system.

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

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	40.000	35.000	75.000
Graduate Students	10.000	22.000	24.000	56.000
Undergraduate Students	3.000	3.000	4.000	10.000
Total Salaries and Wages	13.000	65.000	63.000	141.000
Fringe Benefits	0	8.000	7.000	15.000
Total Salaries, Wages and Fringe Benefits	13.000	73.000	70.000	156.000
Equipment	20.000	30.000	40.000	90.000
Travel	2.000	2.000	4.000	8.000
Materials and Supplies	6.000	5.000	5.000	16.000
Other direct costs	0	0	0	0
Total direct costs	41.000	110.000	119.000	270.000
Indirect costs	10.185	38.800	38.315	87.300
Total direct and indirect costs	51.185	148.800	157.315	357.300

References

[1] D. Peralta, M. Martinez, R. Miquel, *"Top Mass Measurement at the $t\bar{t}$ Threshold*, in the Proceedings of the Linear Collider Workshop 1999, Sitges, Spain. Also availalable from `http://www.desy.de/~lcnotes/`.

[2] P. Garcia, W. Lohmann, A. Rasperezea, *"Measurement of the Higgs Boson Mass and Cross section with a linear e^+e^- Collider"*, LC-PHSM-2001-054, available from `http://www.desy.de/~lcnotes/`.

[3] G. W. Wilson, *"Precision Measurement of the W Mass with a Polarised Threshold Scan at a Linear Collider"*, LC-PHSM-2001-009, available from `http://www.desy.de/~lcnotes/`.

[4] L. Arnaudon *et al.*, *"Accurate determination of the LEP beam-energy by resonant depolarization"*, Z. Phys. **C66** (1995) 45.

[5] C. Yan *et al.*, *"Superharp: A Wire scanner with absolute position readout for beam energy measurement at CEBAF"*, Nucl. Instrum. Meth. **A365** (1995) 261.
I.P. Karabekov, *"High precision absolute measurement of CEBAF beam mean energy"*, CEBAF-PR-92-004, March 1992
P. E. Ulmer *et al.*, *"Absolute Beam Energy Determination at CEBAF"*, IN2P3 note PCCF/RI/9318, 1993.

[6] J. Kent *et al.*, *"Design of a Wire Imaging Synchrotron Radiation Detector"*, SLAC-PUB-5110, January 1990.

[7] E. Torrence, *“Determination of the LEP Beam Energy”*, Proceedings of the International Europhysics Conference on High Energy Physics, Tampere, Finland, 15-21 July 1999, edited by K. Huitu, H. Kurki-Suonio and J. Maalampi, IOP Publishing (Bristol, UK);
B. Dehning, *et al.*, *“Status of the LEP-2 Spectrometer Project”*, CERN-SL-2000-038-BI, July 2000, in Proceedings of the 7th European Particle Accelerator Conference, Vienna, Austria, 26 - 30 June 2000. European Physical Society, Geneva, 2000.

[8] T. Mattison, *”Vibration Stabilization R&D at the University of British Columbia”*, published in Proceedings of the 22d Advanced ICFA Beam Dynamics Workshop on Ground Motion in Future Accelerators, Stanford Linear Accelerator Center, Stanford CA, Nov. 6-9, 2000, ed. A. Seryi, p. 567-577 (2000).

[9] T. Slaton, G. Mazaheri, and T. Shintake, *“Development of Nanometer Resolution C-Band Radio Frequency Beam Position Monitors in the Final Focus Test Beam”*, SLAC-PUB-7921, August 1998.

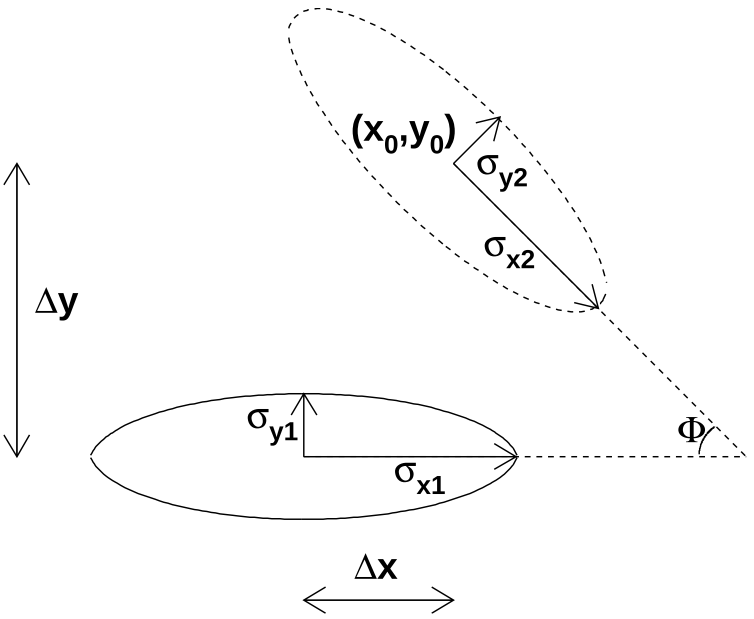

Figure 1: The seven transverse degrees of freedom in the beam-beam collision.

2.2 Coherent and incoherent beamstrahlung at the LC

Personnel and Institution(s) requesting funding

Ivan Avrutsky, Giovanni Bonvicini, David Cinabro, Mikhail Dubrovin, Wayne State University

Project Leader

Giovanni Bonvicini
giovanni@physics.wayne.edu
313-577-1444

Project Overview

One of the greatest challenges for the successful operation of a Linear Collider (LC) will be to monitor the beam-beam collision. A device which directly observes the transverse sizes of the beams, their offsets, and relative orientation at the collision point and which can be used as soon as the machine turns on with "weak" beams would be an invaluable monitoring and diagnostic system for the LC. Fig. 1 shows the seven $transverse$ degrees of freedom (dof) that can affect the beam-beam overlap and therefore the luminosity.

We have described a technique using wide angle beamstrahlung photons [1]-[4] that passively and precisely observes the beam-beam collision region and measures the transverse sizes, offsets and orientations with an accuracy better than 10%. This technique is the only one known that can map six of the seven dof [2], and it is also in advanced state of testing at CESR.

Beamstrahlung photons preserve in their polarization information about the forces and torque exerted by one beam on the other. This information is presented concisely in the beamstrahlung diagram which can be used to study and optimize the delivered luminosity [2].

We obtained a three year NSF Major Research Instrumentation grant in September 2001 to build a device to study large angle beamstrahlung at CESR. We installed in June 2002 a single-arm, one PMT prototype in the CESR/CLEO interaction region at an angle of 11 mrad from the beam axis. We obtained data by varying the observation angle, the beam energy, the PMT spectral response (visible, red, or infrared), and the beam-beam offset. We have developed techniques to point the device, which has an angular acceptance of approximately 2×2 mrad^2, to the IP and observe that backgrounds are consistent with our predictions. Specifically in the infrared at nominal CLEO-c conditions we expect the signal rate to be of order $10^2 - 10^3$ times the background.

Following the successful testing, in July 2003 we installed the first 1/4 of the full device and we will take data as soon as the CESR beams attain sufficient intensity. Things to do include

1. observation of large angle beamstrahlung (this depends solely on attaining a beam current of order 30% of the nominal current)
2. full installation of a four armed system as described in [4]
3. construction of the beamstrahlung diagram and confirmation of its properties
4. integration of the beamstrahlung system into CESR/CLEO operations to maximize delivered luminosity

There is a potentially broad beam physics program attached to the CESR device, including the study of the beam-beam limit and, with the addition of fast-gating electronics, bunch-to-bunch differences. We plan to buy some of such electronics with the funds requested here as this electronics is a must for the LC, and test and use it at CESR. At the NLC, the bunch-to-bunch spacing is 1.4 nsec, to be compared with 14 nsec at CESR. If we will develop a coherent beamstrahlung detector for CESR, as described below, we will need reuse the fast-gating electronics for that application as well.

Our recent studies have focused on beamstrahlung at the LC. Our findings are described in Ref.[5]. We compute a strong visible signal at the NLC, and a full detector simulation will be performed next. The LC environment is different from CESR in that the beams will jitter from one collision to the next. Ref. [2] assumed the steadily varying, continously monitored CESR beams ("beam-beam drift"). The impact of jitter is to reduce the dimensionality of the monitored dof from six to four [5].

Another problem we have noted is that, due to the overall cubic dependence of the signal on the current, visible beamstrahlung does not lend itself to the study of the machine during early turnon. To make up for the loss of information, and the lack of signal early in the game, we have introduced the concept of monitoring the coherent, microwave part of the beamstrahlung spectrum. Coherence occurs at wavelengths longer than the bunch length *when the beams have a non-zero offset at the collision point*. A system that is sensitive to coherent beamstrahlung will provide many benefits including sensitivity to "weak" (low current, high-size) beams and the ability to measure the bunch length by studying the wavelengths of the coherent radiation. Coherent beamstrahlung power, for equal, weak beams colliding with varying offsets, is shown in Figure 2. Ref. [5] notes that one of the advantages of coherent beamstrahlung is that the rates are so abundant that they can be considered free of background from any source of synchrotron radiation.

Note that a measurement of the discrete wavelength pattern of coherent beamstrahlung determines the bunch length and the coherent power is enhanced my many orders of magnitude over the incoherent. A system sensitive to coherent beamstrahlung will be sensitive at low beam currents due to the power enhancement and will be able to measure bunch lengths with high accuracy by observing the power spectrum. Ref. [5] concludes that coherent beamstrahlung adds two extra dof to the information provided by visible beamstrahlung, effectively recovering almost complete visualization of the beam-beam interaction.

We have also continued development of the design of an incoherent beamstrahlung detector for the NLC, as described in our presentation at the NLC workshop in Arlington, January 2003.

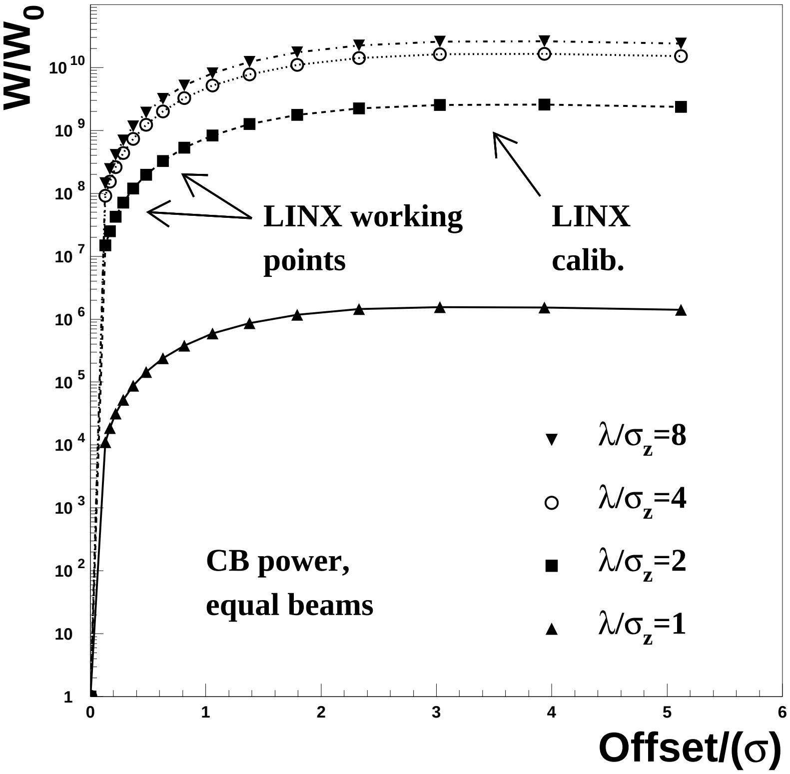

Figure 2: CB yield as a function of the beam-beam offset. The simulations were done with NLC nominal conditions, but weaker beams ($N_1 = N_2 = 0.3 \times 10^{10}, \sigma_{y1} = \sigma_{y2} = 19$nm). Plots are shown for four different wavelength-beam length ratios. The LINX working points are where one may measure beam jitter, and calibrate the device. The markers locate the points where the simulation was performed.

Given the chance, LINX[6] is a perfect opportunity to pioneer a coherent beamstrahlung detector, because of the very short beam length, and the LINX major goal of measuring beam jitter at the nanometer level (which this device can do accurately and conclusively).

If LINX does not go forward, we may consider trying for first detection at CESR. Here this device would be less useful (mostly replicating the information of the present beamstrahlung detector) and the EM wave detection (microwave versus far infrared) different from the LC case. However, a preliminary survey of the CESR beam pipe has shown an excellent location at 3m from the IP, where background RF (from the beam charge image, and surrounding accelerator components) is expected to be very low. We note that the location has button-shaped beam position monitors (BPM), and we are considering doing exploratory work there by studying the frequency spectrum of those BPMs.

The SLAC Test Beam facility (FFTB) may prove useful for evaluating incoherent beamstrahlung backgrounds at the linear collider. Incoherent beamstrahlung backgrounds were calculated reliably within one order of magnitude at both the SLC and at CESR, but similar calculations for the NLC are less mature. Backgrounds to coherent beamstrahlung are dominated by RF generation near the microwave detector (most notably discontinuities in the beam pipe), so the FFTB will be an unreliable predictor of the background at the linear collider. Nevertheless, we will follow our CESR experience in detecting coherent radiation using BPMs with exploratory work at the FFTB in 2006. The instrumentation we propose has no real precedent and we wish to have proof positive that there are no unexpected problems.

FY2004 Project Activities and Deliverables

Work will be continuing on the funded MRI incoherent beamstrahlung system at CESR. We will complete a preliminary design for an LC beamstrahlung monitor system including both incoherent and coherent beamstrahlung radiation detectors, which have to share the same solid angle (approximately from 1 to 1.5 mrad).

FY2005 Project Activities and Deliverables

Continue design and simulation studies for an LC beamstrahlung monitor system. Purchase and test fast-gating electronics, a common need for the NLC and CESR. Analyze the frequency spectrum of CESR BPM, to study coherent beamstrahlung.

FY2006 Project Activities and Deliverables

Complete design for both visible and coherent beamstrahlung detector for the LC. Install and operate fast electronics at CESR. Use the incoherent CESR prototype at the FFTB, and explore coherent backgrounds using experience with BPMs at CESR.

Budget justification

We need 50% of a postdoc to perform the background simulation and the optics optimization for both detectors. The challenge for the visible detector is in background minimization (several methods possible, see Ref.[5]), detector pixelization, and optics. The challenge for the coherent detector is in detector choice, and in designing a fast DAQ system with a dynamic range of at least eight orders of magnitude. We also need to make sure that the large RF power associated with the beam charge image does not induce a large noise.

In year 1 some travel money. In year 2 travel money, 0.5 postdocs and equipment money for fast-gating electronics. In year 3 travel money and 0.5 postdocs.

Indirect costs are 51% of non-equipment costs.

Three-year budget, in then-year K$: Wayne State University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	23.000	24.000	47.000
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	23.000	24.000	47.000
Fringe Benefits	0	5.451	5.688	11.139
Total Salaries, Wages and Fringe Benefits	0	28.451	29.688	58.139
Equipment	0	25.000	0	25.000
Travel	5.000	5.000	10.000	20.000
Materials and Supplies	0	0	0	0
Other direct costs	0	0	0	0
Total direct costs	5.000	58.451	39.688	103.139
Indirect costs	2.550	17.060	20.241	39.851
Total direct and indirect costs	7.550	75.511	59.929	142.990

References

[1] G. Bonvicini and J. Welch, Nucl. Inst. and Meth. 418, 223, 1998.

[2] G. Bonvicini, D. Cinabro and E. Luckwald, Phys. Rev. E 59: 4584, 1999.

[3] G. Bonvicini, CESR Colliding Beam Note, CBN-98-12.

[4] N. Detgen *et al.*, CESR Colliding Beam Note, CBN-99-26.

[5] G. Bonvicini, N. Powell, hep-ex/0304004, submitted to Phys.Rev. STAB.

[6] `http://www-project.slac.stanford.edu/lc/linx/`

3 Vertexing

3.1 Development and design of an LC ASIC for CCD readout and data reduction

Personnel and Institution(s) requesting funding

Boston University, Physics Department: Ulrich Heintz (assoc. professor)

University of Oklahoma at Norman, Department of Physics: Patrick Skubic (professor), George Boyd (engineer)

Collaborators

William Wester, Fermilab
John Jaros, SLAC
Jim Brau, U. of Oregon

Project Leader

Patrick Skubic
pskubic@ou.edu
(405) 325-3961

Changes Since Preliminary Project Description

During the first year, in addition to developing ASIC specifications, we will establish a detailed hardware development plan and an engineering management plan that specifies the roles of Oklahoma, Boston U., SLAC, and Fermilab. The responsibilities and contributions of engineers at the three institutions such as G. Boyd (OU) will be defined. Hardware development will be deferred until a clear plan for the project has been developed. Work will focus on designs suitable for the forward tracking region. An irradiated CCD detector of the SLD design has been successfully read out at OU.

Project Overview

A high-resolution vertex detector is a crucial component of the detector for a future linear collider. An impact parameter resolution $\sigma \approx 5\mu\mathrm{m} \oplus 10\mu\mathrm{m}\,\mathrm{GeV}/p\sin^{3/2}\theta$ is desired both in $r-\phi$ and z for flavour tagging that identifies tracks coming from primary, secondary or tertiary vertices created by the decay of particles in an event [1]. Charge coupled devices (CCD) are the most established technology for large-scale pixel vertex detectors. The SLD experiment has succesfully operated a 307 Mpixel CCD vertex detector [2]. The major challenges for a CCD based vertex detector at a future linear collider are in three areas:

- reducing the amount of material by thinning the substrate;
- improving radiation hardness;
- increasing the readout speed.

This proposal will address the third challenge - readout speed. We propose to develop a readout system that will demonstrate the feasibility of use of CCD's at the LC, and could lead to designs for specific experiments. Other technologies that potentially have resolutions competitive with CCD's may also be investigated. We will collaborate with groups in the US and Europe that are developing CCD detectors for the LC. We will read out the CCD's being studied by the Oregon/Yale group, and those under development for TESLA by the Linear Collider Flavor Identification (LCFI) Collaboration in Europe. Discussions with both groups has been started.

For the vertex detector of the SLD experiment, VXD3, there were 307 million CCD pixels [2]. The electronic circuitry that was used to handle this large number of pixels was complicated, involving at least 8 to 10 FPGA chips that were on FASTBUS modules. Readout of the SLD vertex detector took about 200 ms. For a linear collider application this time must be reduced by three orders of magnitude. This challenging goal will require a long-term R&D effort. To be able to read out the LC vertex detector it will be necessary to suppress pedestals on detector and replace some (or all) of the FASTBUS module functionality with much smaller and faster circuits, possibly contained in a single chip. A parallel readout architecture will have to be implemented.

We propose an R&D program that starts with the detailed study of the present VXD3 design developed at SLAC, and other pixel detectors to understand them thoroughly and will work in collaboration with SLAC and Fermilab to develop ASIC's with improved performance. The proposed work would lead to the design of a highly efficient system, which can be used to improve the electronic performance and hence the accuracy of the detector. In order to test our chips, we propose developing a DAQ test station suitable for detector and readout bench/beam tests. During the past summer, with the help of the U. of Oregon group, an irradiated CCD detector of the SLD design was successfully read out at OU. Clock signals were provided by a pattern generator and arbitrary waveform generators. This provided a flexible way to investigate the CCD performance and we were able to obtain valuable experience with CCD detectors for the first time. The output waveforms for each row were stored on a digital oscilloscope. The proposed DAQ system will allow readout tests with our ASIC chips to be done on prototype CCD's provided by the LCFI and Oregon/Yale collaborations.

Recently, J. Jaros proposed a layout incorporating forward CCD layers consisting of disks perpendicular to the beam line. This layout has the advantage of 10% larger solid angle coverage and minimizes material traversed by forward tracks, thus improving impact parameter resolution. The work proposed here will focus on designs suitable for the forward tracking region, in contrast with the LCFI group which is focusing on central tracking (barrel) designs. This work builds on the experience we obtained while working on the ATLAS forward (disk) pixel detectors.

A complementary proposal will be submitted to the DOE LC R&D consortium by OU faculty member M. Strauss to perform simulations emphasizing the forward tracking requirements. He is well suited to this task since he developed CCD vertex detector tracking software while a member of the SLD collaboration.

This effort builds upon previous VLSI work at University of Oklahoma. Five EE Masters students completed theses on VLSI related projects as members of our group. This includes the complete design, fabrication and testing at OU of 4 generations of a mixed-mode analog multiplexer IC, the VAMUX, which was used in the CLEO III, silicon sensor QA system. Three students contributed to the development of the ATLAS pixel detector front-end readout chip, in collaboration with LBNL. We have educational licenses for Cadence and other design tools.

We have had considerable experience with Maxwell Spicelink, which is a software package which can be used extract the L, C and R parameters of metal traces and their electromagnetic interactions with surrounding materials, such as Si and dielectrics. Maxwell creates a Spice model of the circuitry from a 3-D drawing by solving the field equations using finite element analysis. This spice model can then be used in circuit simulations. These simulations would be very useful in evaluating designs of CCD's that can be read out at very high speeds, such as proposed for TESLA.

Boston University has previous experience with irradiation tests, design, and construction of the silicon strip detector for DØ and high-speed digital electronics for the level 2 silicon track trigger for

DØ. We will draw on the Electronics Design Facility at Boston University [3] as a resource, which has extensive experience in FPGA design (DØ, CMS) and ASIC design (ATLAS). The facility also provides access to the advanced design tools required, such as Mentor and Cadence.

FY2004 Project Activities and Deliverables

Presently, the VXD3 layout consists of three barrels with a total of 96 CCDs on 48 ladders with 4 outputs per CCD yielding a total of 384 outputs. These analogue outputs are digitized and applied with a clocking signal and a bias supply at the front-end (F/E) electronics whereas the FASTBUS modules are used for managing data acquisition and providing timing and control functions. The FASTBUS data acquisition modules are placed at a distance of 50 m from the F/E boards and are connected by optical fibers. For the SLD vertex detector, disruptions in the data link occurred during accelerator operation. For reduction in the amount of devices used and to make the circuit smaller for subsequent improvement in the data processing speed and reliability, we would like to develop a new design. Replacing FASTBUS module functionality with with smaller chips will enable us to place them on the barrel itself, close to the F/E hybrids. This will also make it inaccessible after detector installation, so it has to be completely reliable and able to withstand the radiation environment.

The objective for the first year will be to develop a set of specifications for the ASIC such as modularity, number of gates required for the entire operation and the identification of the design methods and development tools that are appropriate for this project. We will establish a detailed hardware development plan and an engineering management plan that specifies the roles of Oklahoma, Boston U., SLAC, and Fermilab. The responsibilities and contributions of engineers at the four institutions such as G. Boyd (OU) will be defined. We will study the use of ASIC's and FPGA's to optimize the design for the LC. The specifications will be developed in close coordination with the Oregon/Yale and LCFI groups working on CCD detector development.

FY2005 Project Activities and Deliverables

During the second year the engineers at all four institutions will collaborate in the development of a prototype readout chip for CCDs, following the specifications that were developed in the first year.

In order to test prototype vertex detector elements and/or readout chips a simple data acquisition system is required, that can be operated with minimal infrastructure requirements. The Fermilab Computing Division ESE Group has developed a general purpose set of PCI Test Adapter Cards for the BTeV experiment [4][5] that will form the basis of the BTeV pixel detector test stands. These cards are also used to test the SVX4 readout chip for the silicon strip detectors for CDF and DØ. These cards feature large FPGAs that can be programmed to interact with the device to be tested. It seems that these boards could be very useful for linear collider vertex detector test stands as well. This would mainly be done by the Boston group.

We propose to obtain a few sets of these boards and assemble a test DAQ system, using a PC provided by Boston University. We will understand the capability of the system and learn how to program it. By the end of the second year we intend to have the system running in a sample data acquisition application. This may require the design of an additional interface card for the specific detector. This project is well suited in scope for a graduate student.

FY2006 Project Activities and Deliverables

During the third year the design of the readout chip will be finalized using the experience gained from the prototype tests during the previous year. The ultimate goal is to obtain a functional design for a readout chip that establishes the technical feasibility and can serve as the starting point for a production design.

Budget justification

Boston University: We ask for support for a graduate student, who will work 50% on this project. The other 50% of effort of the student will be on DØ for thesis research. This project will provide the hardware experience that is a crucial part of graduate education in particle physics. The graduate student is charged at the rate for graduate assistentships set by the BU College of Arts and Sciences for 2003/04 ($1875/month), increased by an estimated 5% per year thereafter. Half the yearly health insurance premium ($488 in FY2004, 10% increase per year) for the graduate student is included in budget item G6. We are also asking for support for 350 hours of electrical engineering labor in years 2 and 3 at the current subsidized EDF rate of $40/hour (in the other direct costs category). We request travel support for about three trips each in years 1 and 2, and five trips in year 3 to Fermilab or other collaborating institutions for meetings. Indirect costs are calculated at BU's rate of 61.5%. The materials budget includes one set of PCI Test Adapter boards ($2000/set) and funds for an interface card ($2500) in the second year and $2500 in the second and third years for fabrication of readout chip prototypes.

University of Oklahoma: We request a modest amount of support to fund an Electrical Engineering Graduate Research Assistant. (A small tuition remission fee is listed under other direct costs.) An EE graduate student, P. Kshirsagar, has been involved in development of this proposal and would like to use this project as the basis for her thesis. Our electronics engineer, G. Boyd, who is supported by our operating grant, will also participate in the design, fabrication and testing for this project. Fermilab will contribute to the design effort. We are requesting equipment funds for chip fabrication through MOSIS and readout electronics to support development. We request travel funds to allow us to make six round trips per year to Fermilab for meetings with collaborating physicists and engineers from Fermilab and BU. Indirect costs (IDC) are calculated using the OU rate of 48% excluding equipment. OU charges IDC at the rate of 48% on the first $25k of the subcontract with BU.

Three-year budget, in then-year K$: Boston University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	11.250	11.813	12.404	35.5
Undergraduate Students	0	0	0	0
Total Salaries and Wages	11.250	11.813	12.404	35.467
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	11.250	11.813	12.404	35.467
Equipment	0	0	0	0
Travel	1.000	1.200	2.400	4.600
Materials and Supplies	0	7.000	2.500	9.500
Other direct costs	0.488	14.536	14.590	29.614
Total direct costs	12.738	34.549	31.894	79.181
Indirect costs	7.834	21.248	19.615	48.697
Total direct and indirect costs	20.572	55.797	51.509	127.878

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

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	12.000	13.000	14.000	39.000
Undergraduate Students	0	0	0	0
Total Salaries and Wages	12.000	13.000	14.000	39.000
Fringe Benefits	0.828	0.897	0.966	2.691
Total Salaries, Wages and Fringe Benefits	12.828	13.897	14.966	41.691
Equipment	0	10.000	15.000	25.000
Travel	0.740	5.034	4.688	10.462
Materials and Supplies	0	0	0	0
Other direct costs	0.840	0.910	0.981	2.731
Subcontract (BU)	20.572	55.797	51.509	127.878
Total direct costs	34.980	85.638	87.144	207.762
Indirect costs	6.512	9.087	9.433	25.032
Subcontract indirect cost	9.875	2.125	0	12.000
Total indirect costs	16.387	11.212	9.434	37.033
Total direct and indirect costs	51.367	96.850	96.578	244.795

References

[1] J.Brau et al., “Linear Collider R&D”, `http://blueox.uoregon.edu/~jimbrau/LC/LCrandd.ps`.

[2] K. Abe, et al., ”Design and Performance of the SLD vertex detector: a 307 Mpixel tracking system”, Nucl. Instru. and Meth. A400 (1997) 287-343.

[3] see web page at `http://ohm.bu.edu/edf.html`.

[4] K. Treptow, G. Deuerling, “PCI Test Adapter Card”, `http://www-ese.fnal.gov/eseproj/BteV/TestStands/PCI_Test_Adapter.doc`.

[5] J. Andresen et al., “Programmable Mezzanine Card (PMC)”, `http://www-ese.fnal.gov/eseproj/BTeV/TestStands/PMC/Prgm_MezzanineCard.pdf`.

3.2 Study of the Mechanical Behavior of Thin silicon and the Development of hybrid silicon pixels for the LC

Personnel and Institution(s) requesting funding

Purdue University: Daniela Bortoletto (Professor), Ian Shipsey (Professor), Kirk Arndt (Mechanical Engineer)

Collaborators

FERMILAB: Simon Kwan, Jim Fast, Cristian Gingu , William Wester

Project Leader

Daniela Bortoletto
daniela@physics.purdue.edu
(765) 494 5197

Project Overview

One of the main objectives of the linear collider is the measurement of the Higgs couplings. This requires excellent parton flavor identification. Moreover the LC physics relies on the studies with spin-polarized beam which will generate events in the forward-backward region where tracks traverse more material. Therefore it is important that the LC tracking and vertexing systems achieve excellent momentum resolution even in the forward region and for low momentum tracks, good pattern recognition, and extremely precise impact parameter resolution to distinguish secondary and tertiary vertices for flavor tagging. R&D is necessary to substantially improve the vertexing and tracking subdetector performance that was achieved for LEP/SLC to cope with increased jet multiplicity, higher track density in more collimated jets and larger backgrounds[1].

Material minimization is important both to achieve excellent impact parameter resolution and for the precise measurement of low momentum tracks. Therefore it impacts both silicon pixels that provide precise space points near the interaction region and a silicon microstrip tracker further from the primary interaction region, and the measurement of tracks at small angle in the forward region. Hybrid pixels are one of the options under consideration in the Tesla TDR[1] for the vertex detector and the first three planes of the forwad tracker. The hybrid pixel systems under construction for the LHC experiments have a material budget of $\approx$ 1.7 % /layer. The material budget can be reduced to $\approx$ 0.2 %/layer for LC application by connecting 100 μm ($\approx$ 0.1% X_0) thin sensors to readout chip electronics back thinned to 50 μm. The material budget is then comparable to a CCD system when the cryostat is taken into account. In the case of a silicon microstrip tracker for the LC, the momentum resolution of 1 GeV/c tracks achieved by a 5 layer silicon device improves $\delta p_T/p_T$ from $\approx$ 0.2% to 0.07% if the three inner layers use 200 μm thin silicon strip sensors instead than standard 300 μm thick sensors.

The goal of this proposal is the investigation of the best methods to produce and mechanically support thin silicon sensors for Linear Collider(LC) tracking and vertexing applications. The most important issue is the quality of the detector performance versus time and cost required for production. Issues of quality and cost can only be addressed in close collaboration with industrial partners. Purdue has already started a collaboration with Micron Semiconductor to explore thin silicon applications for future upgrades of the LHC (SLHC) since thin silicon requires smaller depletion voltage and therefore it is more radiation hard than standard $\approx$ 300 μm thick silicon. This development has been funded by the DOE ADR program. We will use the same masks and the same processing to produce sufficient silicon sensors to allow for bump bonding studies at no cost to this proposal. The masks, which have been already submitted to Micron, contain both silicon microstrip and pixel sensors matching CDF run 2b microstrip sensors and the CMS pixel layout respectively. The sensors are designed to be read-out with electronics already developed for the LHC and run 2b of the Tevatron. Although, the design of the sensors is not optimized for LC operation, quality, cost, and bump bonding yield are approximately independent of the readout chip and the sensor design. By using a common sensor design we will perform a cost effective investigation of the feasibility of thin silicon technology for LC. However there are insufficient funds available in the ADR alone to develop bump bonding of thin silicon which is essential for hybrid pixel development and we request these funds in this proposal. Since the development of bump bonding of thin silicon is a considerable fraction of the funds requested we concentrate our discussion on the hybrid pixel system. We estimate that a 4-5 year development program in close association with a company is needed to demonstrate thin high yield affordable bump bonded pixel detectors.

Although most attention world wide is focused on the processing and bump bonding aspects of thin silicon development, the mechanical aspect are frequently overlooked and equally challenging and will require a similar amount of time to develop. We will produce thin silicon sensors which will be bump bonded to existing electronics. These structures will be used to study the mechanical mounting and the stability of thin silicon. The mechanical studies will have an impact not only for hybrid pixels but also for CCDs, silicon microstrip detectors and other attractive thin substrate technologies such as MAPS (Monolithic Active Pixels Sensors). Clearly thin sensors and thin ROCs are crucial to develop a hybrid silicon system for the LC. In parallel and in conjunction with o ther groups in the US, Asia and Europe we will study with Monte Carlo the physics reach of a thin hybrid pixel system at a linear collider and optimize its design. Finally at an appropriate future time we expect to be actively engaged in comparing the sensor technologies proposed here with competing technologies.

Physics Motivation

Physics studies have shown that jet flavor identification with high efficiency and purity is a critical element in the full exploitation of the physics potential of the Linear Collider (LC). Jet flavor identification can be achieved in the highly collimated jets expected at the LC with precise vertex detection based on pixel detector technology achieving an impact parameter resolution of

$$\sigma_{r\phi,z}(IP) = 5\mu m \oplus \frac{10\mu m GeV/c}{p\sin^{3/2}\theta}$$

or better. In this expression the first term depends on the detector intrinsic single point resolution and geometry while the second term accounts for multiple scattering.

Charged Coupled Devices (CCD) operating at the SLD have demonstrated a resolution and a material budget close and even superior to the above requirement. Improvements are needed to achieve the readout speed required for operation at future machines such as TESLA where the single bunch crossing will take place every 330 ns. For CCDs another area of concern is radiation tolerance. Studies are taking place to evaluate the radiation damage of the SLD CCDs.

Several studies have taken place in Europe aimed at investigating an alternative approach to jet flavor identification based on solid-state hybrid pixel detectors. This technology, used for vertex detectors in the CMS and Atlas experiments at the LHC, has the advantage of fast time stamping, sparse data read out, and excellent radiation tolerance. Assuming a three layer hybrid pixel system, with the first sensitive layer at 1.2 cm radius from the interaction point and the outmost layer at 10.0 cm radius, the desired impact resolution could be achieved with a single point resolution of $\approx$ 7 μm and a material budget of 0.5%X_0 for each layer[2]. This material budget assumes standard $\approx 300\mu$m sensors connected to readout chip electronics back thinned to $\approx$ 50 μm.

Research and Development in the following areas are required for further improving this technology for LC application :

1. Improvement in the point resolution, which is currently limited by the pixel readout (ROC) dimensions of 50 μm$\times$ 300 μm
2. Reduction in material. The standard thickness in silicon processing is about 300μm.

Even with the current ROC cell size, a $\approx$ 7 μm point resolution can be achieved by adopting an interleaved pixel read out as shown in [2]. This approach is similar to charge sharing through capacitive coupling in silicon strip using intermediate strips [3] and it has already produced interesting results. An alternative but more attractive option is to take advantage of the advances in submicron technology for fabricating the ROC which should allow the hybrid pixel to achieve a smaller cell dimension in the near future.

A reduction in material can be achieved directly by fabricating thin silicon sensors and read-out, or by thinning the substrates after processing. The Atlas and the BTeV collaborations have already performed R&D on sensors and ROC thinning techniques for hadron colliders applications. Our proposal will investigate for the first time the production and bump bonding of ultra-thin 100 μm pixel sensors to electronics back thinned to 50 μm. For the LC application the reduction in the material budget is necessary to limit multiple scattering and provide excellent impact parameter resolution.

Current Status of Research on Thin Silicon Sensors at Purdue

Using DOE ADR funding, the Purdue group has explored the capabilities of several vendors to produce thin silicon sensors and received quotes from two vendors, SINTEF and MICRON. Both vendors were extremely interested in developing this new product line since pixels are expected to be a common feature of future high energy physics detectors. After reviewing vendor capabilities we have submitted a mask design to MICRON.

Bump bonding is beyond the scope of the ADR proposal but it is crucial for hybrid pixel systems. MICRON is willing to contribute funds for new equipment to develop bump bonding capabilities to the ROC chip. This development could be important since it would streamline pixel production and avoid sending the sensors to a separate vendor for bump bonding.

MICRON expects to be able to provide thin silicon wafers in the following thicknesses: 65, 80, 100, 150 and 200 μm in 4 inch technology. The six inch technology will be limited to the last three options. The ultra thin wafers are especially interesting both for the SLHC and LC. For example a detector 50 μm thick, with $\rho = 50\Omega cm$ will deplete at 200 V. The material would undergo type inversion at a fluence of 10^{15} particles/cm^2 which is well beyond the LC fluence.

The plan will be to first produce the sensor wafers at the aluminum stage and to work with an external bump bonding company. MICRON will then develop the under bond metallization process and then provide bump bonding to the readout chip. The step will first require metallization of the sensors with barrier metals to prevent aluminum spiking. To develop the bump bonding, MICRON will also have to purchase or rent a Karl Suss Flip-Chip machine. This development will take place next year if we receive Linear Collider funding.

Unique Facilities at Purdue

Fermilab and Purdue University are collaborating in the work proposed here. The group at Purdue University has already received funding through the DOE ADR program to study thin silicon sensor production. The proposed effort builds upon our experience in design and testing of silicon microstrip and silicon pixels for CDF and CMS. We have access to CADENCE design tools and DESSIS simulation tools. The mechanical aspects of the project build upon our experience in the mechanical design, fabrication, and assembly of the silicon detector for CLEO III, and the mechanical design and prototyping of parts of the CMS forward pixel detector.

The detector facility at Purdue University contains two fully equipped clean rooms for the design, testing and assembly of detectors for High Energy Physics. These clean rooms are part of a complex dedicated to microstructure detector development and fabrication including silicon strip and pixel devices and micro pattern gas detectors. The total clean room space is 3000 sq ft in three laboratories containing a CMM, wirebonder, electrical testing equipment, probe stations, optical tables, microscopes and high precision measuring devices. The labs are fully equipped with computer facilities for control, data acquisition and analysis. The labs have both temperature and humidity control and HEPA filtering of the airflow. Included in the clean rooms is additional space of class 1000. In a separate location there is a detector irradiation facility with an X-ray source and an ultra clean gas delivery system used for the development and testing of micro pattern gas detectors.

Other technical resources are also available, such as machine and electronic shops within the physics department, a central machine shop and state of the art facilities on campus, such as SEM, TEM (Transmission Electron Microscopy) and EDS (Energy Dispersive Spectroscopy). In addition to the technical staff, an engineer and technician, there is the normal complement of graduate students and research associates working on specific projects. There is also an exceptional pool of talented undergraduates who work on R&D and detector construction projects.

FY2004 Project Activities and Deliverables

About 20% of our effort during FY2004 will be dedicated to collaboration with European groups to establish the physics reach of a hybrid pixel system for the LC. This will include a focused simulation program to estimate the performance of a thin hybrid pixel system in collaboration with the LC tracking and vertexing simulation group. Simulation of the interleaved pixel layout and/or smaller cell size will also be conducted. We will also study the impact of thin silicon on the performance of the forward tracking system.

We expect to receive the first thin sensors in 2004. This will enable us to start a serious program of material characterization and evaluation first with microstrip sensors. The investigation of the material and device properties which are necessary to improve device design will require careful device characterization. Simulation will be required to gain a detailed understanding of device behavior and develop predictive tools for improving device design. The tasks needed to complete this characterization and evaluation program are:

- Measurement of the device DC properties
- Characterization of the active volume of the device and optimization of the Charge Collection Efficiency (CCE)
- Tests of the device response and measurement of pulse shape.

The outcome of these studies will be a determination of the minimum thickness that can be achieved in single sided pixel manufacturing. We also plan to start working with Micron to develop the bump bonding of thinned electronics to thin sensors wafers.

The first year deliverable will be a systematic study of the characteristics of thin silicon microstrip sensors and first results from device and physics simulation studies.

FY2005 Project Activities and Deliverables

In the second year we expect to receive the first thin silicon pixel bump bonded to thinned electronics. This will enable studies of the mechanical mounting and the stability of thin silicon hybrid pixels.

1. Studies of alignment and fabrication of low mass support frames will be conducted at Purdue. Metrology of thin silicon samples will be performed during cooling cycles. These will need to be conducted at cryogenic temperatures for CCD applications.
2. Finite Element Analysis (FEA) will be performed at Fermilab to understand the mechanical stability of thin silicon.
3. The Fermilab group will share the results of their R&D studies of thinning the ROC and silicon sensors that they are performing for BTeV. Interleaved pixel sensors, which are available on the BTeV wafers, will be used to build prototypes to gain more experience on the performance of interleaved thin pixels.

We will also continue the simulation of the hybrid pixel configuration.

The second year deliverable will be a systematic study of the stability issues associated with thin silicon hybrid pixels. Information will be gained on the performance potential of interleaved hybrid technology for the LC.

FY2006 Project Activities and Deliverables

In the third year we will continue the simulation effort and the mechanical studies. Systematic studies will be performed with the bump bonded pixels to determine the resolution and charge collection efficiency of the prototype hybrid pixels with cosmic rays, laser diodes, and possibly beam tests. We will compare MC simulations conducted at Purdue to the performance of the pixels readout with the CMS chip.

The third year deliverable will be a first evaluation of the potential gain in resolution that can be achieved with thin, interleaved hybrid sensors. We expect to perform:

- Beam tests for structures wire-bonded to electronics.
- Tests of structures bump-bonded to readout electronics.

- Simulation of charge collection properties of structures, with both two-dimensional and three-dimensional simulation packages, CCE, pulse shape, operating conditions etc.

Many of these investigation will be done in conjunction with studies for the LHC.

Budget justification

We request funds to support 50% of a graduate student. The remainder of the support of this student will come from the Purdue CDF group. The graduate student is charged at the rate set by Purdue University for 2003/2004, increased by an estimated 5% per year thereafter. We also request funds to support 50% of a postdoc during year 2 and 3 of our proposal. The remainder of the support of the postdoc will come from the Purdue CDF and CLEO group. The postdoc and the graduate student will carry out the simulation studies and will evaluate the thin silicon sensors.

We request travel support for about 3 trips each year to institutions working on LC vertexing. We are also asking for equipment items.

First Year Budget

During the first year we request $ 25K to support the development of bump bonding with a vendor.

Second Year Budget

The second year equipment budget will allow Purdue to build a system to study the mechanical issues connected with the thinning of sensors and readout chips. The study will include precision measurement of the stability of the support schemes including temperature cycles. Some of these studies will be conducted with blank silicon and some with sensors built using ADR funds. The graduate student at Purdue will work closely with the Purdue mechanical engineer to perform the temperature cycling studies. Thin sensors provided by the ADR funding will allow a determination of the yield and the minimum thickness that is achievable by the vendors. Finite element analysis (FEA) studies will be carried out by Fermilab personnel supported by Fermilab funding.

Equipment breakdown:

1. **Precision alignment tooling: $1.5K**
   Vacuum holders for sensor/ROC assemblies and holder for support frame that precisely aligns the modules to the support frames. Cost is based on recent experience with similar tooling for CMS pixel R&D efforts.
2. **Fabrication and assembly of a low-mass support frame: $2.2K**
   Support frame will be either beryllium or carbon composite and will need to be of reasonably high precision.
3. **Thinned silicon, 2 batches @ $1K per batch: $2K (at no cost - ADR funding)** Cost estimate is based on previous purchases.
4. **Metrology: $2.0K** This involves modifications to allow us to mount our samples in a dry chamber at low temperature in order to be optically inspected through a window. This will be similar to a chamber built by BTeV for their pixel studies but modified to allow for operation at cryogenic temperature.
5. **Engineering analysis (FEA): $1.5 K (at no cost - supported by Fermilab)** This allows for 30 hours of engineering analysis by the FNAL analysis group.

Third Year Budget

The third year requires support for a cosmic ray and a laser setup with interleaved pixel prototypes matching an existing ROC chip (BTeV or CMS). It also funds the simulation activities that will start at Purdue.

Three-year budget, in then-year K$: Purdue University

Item	FY2004	FY2005	FY2006	Total
Postdoctoral Associate		20.755	21.377	42.132
Graduate Students	9.526	9.812	10.107	29.445
Total Salaries and Wages	9.526	30.567	31.484	71.577
Fringe Benefits	0.451	9.019	9.317	18.787
Total Salaries, Wages and Fringe Benefits	9.997	39.586	40.801	90.384
Equipment	25.000	5.700	10.000	40.700
Travel	2.500	2.500	2.500	7.500
Materials and Supplies	0	0	0	0
Other direct costs	2.384	2.619	2.794	7.797
Total direct costs	39.861	50.405	56.095	146.361
Indirect costs	6.488	21.884	22.517	50.889
Total direct and indirect costs	46.349	72.290	78.612	197.251

References

[1] The TESLA technical design report, `http://tesla.desy.de`

[2] M. Battaglia et al., IEEE Nuclear Science Symposium and Medical Imaging Conference, October 15-20, 2000, Lyon, France, IEEE Trans.Nucl.Sci. 48 (2001) 992- 996; M. Battaglia et al., Proceedings of the 9th Int. Workshop on Vertex Detectors, Lake Michigan MI (USA), September 2000, Nucl.Instrum.Meth. A473 (2001) 79-82.

[3] A Piesert, in Instrumentation in High Energy Physics, New York, World Scientific, 1, 1992

4 Tracking

4.1 Tracking Detector R&D at Cornell and Purdue Universities

Personnel and Institution(s) requesting funding

D. P. Peterson, R. S. Galik, Laboratory for Elementary Particle Physics, Cornell University
J. Miyamoto, I. P. J. Shipsey, Physics Department, Purdue University

Collaborators

none

Project Leader

Dan Peterson
dpp@lns.cornell.edu
(607)-255-8784

Project Overview

Experimental physics goals for a future linear collider create challenging demands on a charged particle tracking detector in regard to both momentum resolution and multi-track separation. Anticipated beam-related background rates place further demands on the detector segmentation. A time projection chamber (TPC) may provide the best combination of detector segmentation and continuous track measurements which would lead to the optimum multi-track separation and noise immunity. However, the segmentation of current technology TPCs is still insufficient for precision reconstruction of linear collider events. In addition, obtaining the spatial resolution necessary to meet the momentum resolution goal is challenging with the current technology.

Events at the linear collider will contain jets with track density on the order of 100 tracks/steradian. Events with this track density have been reconstructed at RHIC experiments and are expected at LHC experiments. However, a tracking goal of the linear collider detector, as described in the “Linear Collider Physics Resource Book” [1], is the precision measurement of jet energies. This measurement requires aggressive multi-track separation in both azimuth and polar angle. TPCs with multi-wire-proportional-chamber gas-amplification and readout, of which the STAR and ALEPH chambers are typical examples, have pad readouts with a pad size on the order of 1 cm in the azimuthal direction. This segmentation is too coarse to provide the multi-track separation required at the linear collider.

Other tracking goals, such as the precision mass resolution of di-leptons in Higgsstrahlung events and the precision end-point momentum resolution in leptonic supersymmetric decays, lead to a desired resolution of $\sigma(1/\mathrm{p}_t)$ of order $10^{-5}\mathrm{GeV}^{-1}$. This momentum resolution can be achieved only if the TPC spatial resolution is of order 100 μm. This spatial resolution is very challenging with multi-wire-proportional-chamber readout TPCs not only because it represents 1% of the pad size, but also because the radial electric field in the vicinity of the amplification wires leads to a significant spatial distortion.

A TPC readout based on a gas amplification micro-structure such as a GEM or MicroMegas promises to provide both improved segmentation and resolution. Segmentation is improved due to a fundamentally reduced transverse signal size; the signal is created on pick-up pads by electron transport rather than induction. The pad size can then be significantly reduced. Spatial resolution is improved due to the reduced signal size and reduced **E** x **B** distortion of the drift path in the vicinity of the amplification. Operation in a high rate environment is simplified because these readout systems naturally suppress ion feedback into the drift volume.

Significant development and operating experience are required before a full-size design for a detector based on a GEM or MicroMegas amplification can be finalized. The physical width of the charge deposition is small compared to the typical readout pad size used in a traditional readout TPC creating a condition where the signal is often observed on only one pad. Without signal sharing, the spatial resolution is degraded. The use of smaller pads to provide signal sharing may require a prohibitive number of instrumented pads and the signal measurement on each pad may then be limited by ion statistics. Several alternatives have been suggested to optimize the charge deposition width for spatial resolution and segmentation, for example, increased spacing between the amplification elements, resistive anode layers, and chevron shaped pads. Each of these may compromise the segmentation or lead to other operational problems. These alternatives are largely untested. Even with many groups working on these problems, the development will take several years and should not be delayed.

The development of large scale manufacturing of GEMs provides another motivation for initializing TPC research as early as possible. As described below, Purdue is involved in several studies of manufacturing techniques for the purpose of providing large scale production of reliable GEMs. It is expected that the GEM manufacturing will require 3 to 4 years of development. A TPC testing program that includes the capability of using interchangeable amplification devices is required as a test bed for the manufacturing development.

We propose to initiate a program of gas chamber tracking detector development. We will study issues of resolution, segmentation, channel count, signal complication, noise, cross-talk, and ion feedback using various readout systems on prototype TPCs.

The TPCs, as well as drift chambers used for track definition, will be built at Cornell. We will test both traditional TPC readouts using anode wire amplification built at Cornell, and alternative TPC readouts using GEM and/or MicroMegas amplification built at Purdue. In studies of the anode wire amplification readouts, we will investigate methods of optimizing the resolution and track separation while varying the wire spacings. These studies will also provide an understanding of the data acquisition (DAQ) system and a baseline for the signal and noise characteristics of the alternative amplification devices. In building and operating the tracking chambers the Cornell group will draw on their extensive experience building drift chambers for the CLEO experiment [2, 3, 4].

GEM and MicroMegas readout modules will be built by the Purdue group who have many years experience developing Micro Pattern Gas Detectors (MPGD) [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. In collaboration with the CERN and Saclay groups, radiation hardness of GEM and MicroMegas foils manufactured at CERN have been studied and excellent radiation hardness has been demonstrated. The first triple-GEM [16] and GEM+MicroMegas detector [17] have been built. The latter has achieved the best signal-to-noise performance in a beam line of any MPGD to date [18] making it very attractive for TPC readout. In addition a new readout mode of a MicroMegas has been developed that promises greater electrical robustness.

GEM manufacturing technology, for readily available samples, has been limited to Kapton lithography. Purdue is involved in several studies of alternative manufacturing techniques. In collaboration with the University of Chicago, a micro-machined large area LEM (large scale GEM) has been built and successfully tested at Purdue. Electrode-less GEMs and MicroMegas, which have greatly reduced material budgets, are also under development. Most recently, the Purdue/Chicago collaboration has worked with the 3M corporation to develop a less expensive, large quantity, manufacturing process for standard GEMs. These have been delivered and tested at Purdue and CERN. Preliminary results indicate that the performance of GEMs manufactured by 3M is indistinguishable from the performance of those manufactured at CERN.

The development of new manufacturing techniques for GEMs and MicroMegas is important because it may provide reduced cost and procurement time for large scale implementations such as a TPC or a hadron calorimeter. Much of this work is at an early stage; extensive R&D and testing, including radiation hardness studies, will be required. Funding exists for this work and we are not seeking additional funding for it at this time. These studies will be performed by many groups, including Purdue, over the next few years. We expect to incorporate each of the successful alternative manufacturing technologies into a TPC readouts. However, in the first instance we will use CERN built devices. This will ensure that TPC readouts can be designed, tested, and will be operational during year one of this proposal.

We also plan to study detectors in a magnetic field equal to that envisioned for the final detector and in a high radiation environment. The Cornell accelerator group will provide a uniform-field, 4 Tesla, superconducting magnet. The utilities to operate the magnet are available at Cornell.

FY2004 Project Activities and Deliverables

In the first year of a staged build-up of the detector program, we will build drift chambers for track definition and a small TPC with anode wire amplification readout. We will install a limited, but expandable, stand-alone DAQ system at Cornell to provide track definition over a small area and readout for a limited number of TPC channels using commercial flash analog to digital converters (FADC). We will demonstrate the resolution of the track definition system. We will use the initial TPC test chamber to understand the FADC DAQ system, study the time evolution of the signals and make limited resolution measurements. After completing measurements on the anode wire amplification readout we will make similar preliminary measurements on a small TPC with GEM readout. First year tests will be with cosmic rays.

The first year deliverable will be the successful operation of the initial TPC.

FY2005 Project Activities and Deliverables

In the second year, we will build a larger TPC which will accept interchangeable readout planes and expand the coverage of the track definition system. We will expand the DAQ system for both the track definition and the TPC to allow study of resolution and noise effects in larger systems. The proposed DAQ system will provide readout for a 256 channel TPC which will allow us to measure tracks in about 20 layers, each about 13 pads wide. The size of this detector will be sufficient for cross-talk studies and to measure the track trajectory with less reliance on extrapolation of the track from the drift chambers. Measuring the track trajectory internally in the TPC provides a more precise determination of the resolution and will be particularly important when measurements are made in a magnetic field. We will continue to use cosmic rays which will be sufficient based on previous experience of making successful measurements of resolution and efficiency using test chambers with smaller detector acceptance [4].

We will study resolution and track separation, as well as signal time development and noise characteristics with several different readout planes installed on the TPC. For the case of readout planes with anode wire amplification, we are particularly interested in increasing the anode wire density while decreasing the anode-cathode spacing. For the cases of readout planes with multiple GEMs, MicroMegas and hybrid amplification, we plan to vary the amplification-stage voltages and spacings and the pad segmentation as a means of optimizing the signal separation and spatial resolution. We will also study the effects of various methods of spreading the signals such as resistive anode layers. Ion feedback suppression, expected to be superior in MicroMegas relative to GEMs, will be measured for each amplification system using a common TPC. Measurements in a magnetic field may be started in the second year but we defer that deliverable to the third year.

The second year deliverable will be a systematic study of the track separation and position resolution with various readout planes.

FY2006 Project Activities and Deliverables

In the third year we will continue the detector studies in a magnetic field and will also make measurements with a large photon background.

The third year deliverable will be the continuation of the systematic study of the track separation and position resolution in a magnetic field.

Budget justification

The first year equipment budget for Cornell provides for a minimal DAQ and HV system to operate the track defining drift chamber and a small TPC. This includes some initial costs associated with the expandable system: a VME crate and a HV frame and HV power supplies. The second year equipment budget for Cornell provides for an expansion of the DAQ for use with a larger test device. The major expenditure is in the FADC modules. As an alternative, it may be possible to use TPC readout electronics developed for the STAR experiment for the readout of a larger test device. This system would provide a reduction in cost and more channels. As the STAR readout is VME based; most of the equipment purchased in the first year for the initial system would be used with this alternative. We will fully investigate the feasibility of using the STAR electronics after the first year. The third year equipment budget for Cornell provides for further expansion of the DAQ system, maintenance of existing equipment and/or the purchase of items not yet foreseen. The Cornell budget includes funds for travel to Purdue as part of the collaborative effort.

Cornell will provide reallocation of resources to this this project in the form of support for research staff (Dan Peterson) and technical staff and machine shop time to construct the chambers. Cornell will provide the custom components to construct the drift chambers. In addition, Cornell will provide the cost of designing and constructing the analysis magnet.

The yearly Purdue equipment budget provides for the purchase of unmounted GEM and MicroMegas devices from CERN and 3M and the manufacture of printed circuit pad readout in the U.S. Purdue is also requesting funding to support two undergraduate students per year at 20 hrs a week, 40 weeks a year. The students will work exclusively on this project. Ian Shipsey has had over twenty undergraduates work with his group since 1992. This has been a very productive arrangement both for the group and the students resulting in several publication [10, 14, 15, 16, 19].

Purdue engineers and post doctoral physicists will work on the design and testing of the devices but derive their salary support from base funding. Machine shop charges will likewise be derived from base funding. Clean-room, testing, and assembly facilities at Purdue will be made available for this work at no charge.

Three-year budget, in then-year K$: Cornell University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	0	0	0
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	0	0	0	0
Equipment	52.000	121.000	74.000	247.000
Travel	2.000	2.000	2.000	6.000
Materials and Supplies	0	0	0	0
Other direct costs	0	0	0	0
Subcontract (Purdue)	34.320	34.320	34.320	102.960
Total direct costs	88.320	157.320	110.320	355.960
Indirect costs	1.160	1.160	1.160	3.480
Subcontract Indirect costs	6.500	0	0	6.500
Total Indirect costs	7.660	1.160	1.160	9.980
Total direct and indirect costs	95.980	158.480	111.480	365.940

Three-year budget, in then-year K$: Purdue University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	16.000	16.000	16.000	48.000
Total Salaries and Wages	16.000	16.000	16.000	48.000
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	16.000	16.000	16.000	48.000
Equipment	10.000	10.000	10.000	30.000
Travel	0	0	0	0
Materials and Supplies	0	0	0	0
Other direct costs	0	0	0	0
Total direct costs	26.000	26.000	26.000	78.000
Indirect costs	8.320	8.320	8.320	24.960
Total direct and indirect costs	34.320	34.320	34.320	102.960

References

[1] “Linear Collider Physics Resourse Book for Snowmass 2001”, CLNS 01/1729.

[2] “The CLEO II detector”, Y. Kubota *et al.*, Nucl. Inst. and Meth. A320 (1992) 66-113.

[3] “The CLEO III drift chamber”, D. Peterson *et al.*, Nucl. Inst. and Meth. A478 (2002) 142-146.

[4] “Progress on the CESR Phase III and CLEO III Upgrades at Cornell”, D. Peterson, Nucl. Phys. B (Proc. Suppl.) 54B (1997) 31-46.

[5] For more information, see the web site, `http://www.physics.purdue.edu/msgc/`.

[6] ”Gas Microstrip Detectors on Resistive Plastic Substrates”, M. S. Dixit et al. Nucl. Inst. and Meth. A, 348 365 (1994).

[7] ”Plastic MSGC’s with two-sided readout”, I. Shipsey Proceedings of the 2nd InternationalWorkshop on MSGC’s Legnaro (1994).

[8] ”Performance of Microstrip Gas Chambers Passivated by Thin Semiconducting Glass and Plastic Films”, M.R. Bishai et al. Nucl. Inst. and Meth. A, 365 54 (1995).

[9] ”Micro Strip Gas Chambers Overcoated with Carbon, Hydrogenated Amorphous Silicon and Glass Films”, M.R. Bishai et al. Nucl. Inst. and Meth. A, 400 233 (1997).

[10] ”Properties of a Moscow Glass Micro Strip Gas Chamber”, E.K.E. Gerndt et al. Nucl. Inst. and Meth. A, 388 42 (1997).

[11] ”An aging study of semi-conductive microstrip gas chambers”, E.K.E. Gerndt et al. Nucl. Inst. and Meth. A, 422 282 (1999).

[12] ”An aging Study of a Gas Electron Multiplier with Micro-Strip Gas Chamber Readout”, J. Miyamoto and I. Shipsey IEEE Trans. NS Vol 46, No. 3 pp 312- 316(1999).

[13] ”An Aging study of Semiconductive Microstrip Gas Chambers and a Gas Electron.Multiplier”, J. Miyamoto and I. Shipsey, Nucl. Phys. B 78. pp 695-702, (1999).

[14] ”An Aging Study of Double GEMS in Ar-CO2”, S. Kane, J. May, J. Miyamoto and I. Shipsey in Proceedings of the IEEE Nuclear Science Symposium, Oct. 2000, Lyon, France. ISBN-0-7803-6506-2(CDrom) ISBN-0-7803-6503-8 (softbound) copyright The Institute of Electrical and Electronic Engineers Inc.

[15] ”An Aging study of a MICROMEGAS + GEM”, S Kane, J. May, J. Miyamoto, I. Shipsey accepted for publication in Nucl. Inst. and Meth. A, (2001).

[16] ”An Aging Study of Triple GEMs in Ar-CO2”, L.Guirl, S Kane, J. May, J. Miyamoto, I. Shipsey, Nucl. Inst. and Meth. A 478 263-266 (2002).

[17] ”A Study of a Combination MICROMEGAS + GEM Chamber in an Argon Carbon Dioxide Gas Mixture” S Kane, J. May, J. Miyamoto, I. Shipsey and I. Giomataris, to appear in Transactions of the Institute of Electrical and Electronic Engineers (2002).

[18] ”A Study of MICROMEGAS with Preamplification by a Single GEM”, S Kane, J. May, J. Miyamoto, I. Shipsey, and I. Giomataris to appear in Nucl. Inst. and Meth. A, (2002)

[19] ”An Aging study of a MICROMEGAS + GEM”, S Kane, J. May, J. Miyamoto, I. Shipsey accepted for publication in Nucl. Inst. and Meth. A, (2002).

[20] ”A New Readout Mode for a MICROMEGAS”, J. Miyamoto and I. Shipsey, submitted to Nucl. Inst. and Meth. A (2002).

4.2 Negative Ion TPC as the LC main tracker

Personnel and Institution(s) requesting funding

Giovanni Bonvicini, Alexander Schreiner, Wayne State University

C. J. Martoff, Rachid Ayad, Temple University

Collaborators

D. Snowden-Ifft, Occidental College

Project Leader

Giovanni Bonvicini
giovanni@physics.wayne.edu
313-577-1444

Project Overview

The novel gas detector technology called Negative Ion TPC (NITPC) is a strong candidate as a main tracker for the Linear Collider. The technique utilizes a special, electronegative gas (NIgas) mixture to transport negative charge from track to detector plane in the form of negative ions rather than electrons. The slow drift speed and strong thermalization of the drifting ions result in a number of advantages important for an NLC tracker. A 1 m^3 NITPC has been working for one year as a directional Dark Matter detector, unattended for weeks at a time, providing proof that the concept works in practice[1]-[2]. A new, larger Dark Matter NITPC was proposed this year. The NITPC has also found applications in national security as a directional neutron detector. Further developments in few-molecule mass spectrometry are also in an advanced state.

The NITPC option provides some unique options for the LC. With the simple geometry described below, and the simulation results presented below, we can list a number of possible advantages for the NITPC as a main LC tracker.

1. better momentum resolution than a regular TPC (e-TPC).
2. potentially less sensitive to space charge, and therefore potentially more robust calibration (this will depend on the type of detector plane. We note below the higher capacitance and lower ionization density of this device).
3. good enough resolution to use in a Small Detector configuration, should solid state options not meet their R&D goals
4. far less material than a e-TPC in the endcap region, improving, for example, W/Z discrimination in the forward region. There are further advantages in chamber thickness due to the low number of channels and cables (a factor of 50 reduction), and lower wire pressure which implies a lighter structure supporting the wire tension load.
5. low cost, due to low number of electronics channels.

The concept can work as well with any of the recently developed microchambers (e.g., GEM or MicroMegas). We note that the tendency of microchambers to spark is strongly suppressed by any NIgas, so that a NIgas can be of practical great help in operating a microchamber. Our gas, CS_2, is also the strongest UV quencher used in gas detectors. Our preliminary GEM tests (Table 1), showing strong gain and quiet operation at a very high voltage, certainly lend credibility to the idea of coupling microchambers and NITPC. Further, the sub-millimeter single electron resolution in the detector plane, available in microchambers, is well matched to the sub-millimeter single ion resolution in the drift direction, that the NITPC provides. Together they would provide extremely fine pattern recognition.

Ultimately, a figure of merit will emerge for the LC main tracker, addressing its cost, momentum resolution and calibration, background tolerance, and radiation thickness. We note that the costs of the device described below are expected to be low, the momentum resolution is certainly excellent, the calibration is potentially more robust, the background tolerance is high (due to the geometry and the light gas mixture) and can be further improved by the SD/ High **B** option, and the radiation thickness is low and distributed reasonably well in θ.

In the last year extensive simulation has been performed and the results support the contention that a NITPC is a superior tracker candidate[3]. The issue of background rejection was tackled by assuming a worst case scenario (TESLA bunch train, low magnetic field, Table 2). At the NLC or JLC the NITPC will always have lower backgrounds than a e-TPC, due to lower gas density (Tables 1 and 2).

The detector model we chose is particularly simple (likely, it can be improved), but we were able to produce significant simulation in a finite amount of time. It is an unusual model compared to e-TPCs. Its main features, and reasons for its choice, are summarized here:

1. the NITPC has 6 detector planes, and 12 drift gaps along the azimuth. Ion drift is not affected by the magnetic field up to 6T, and azimuthal drift provides the best momentum resolution. The axial NITPC showed good momentum resolution but very poor background tolerance. The radial geometry has the same background tolerance as the azimuthal geometry but the worst momentum resolution of the three geometries.
2. The detector plane, as simulated, consisted of a drift grid (not shown in Fig. 1), a set of sense wires, and a double set of daisy-chained pads, one running NW-SE and the other running NE-SW. A hit is defined as a triple coincidence of wire, strip(s) NW-SE, and strip(s) NE-SW.
3. The NITPC was assumed to have 4×10^4 electronics channels, as opposed to 2×10^6 for the e-TPC[4]. Also the sampling rate was assumed to be 10 MHz as opposed to 20 MHz[4].

The electronegative gas parameters are listed in Table 1. The detector parameters, for a NITPC and a comparison e-TPC, are summarized in Table 2. The factor of 100 in longitudinal sampling, compared with the e-TPC, is crucial to understand the difference in performance.

Besides regular backgrounds, the simulation had to address the possibility of combinatorial backgrounds. It was straightforward to show that these backgrounds are small[3]. Further algorithms, currently under development, will optimize pulse asymmetry cuts between strip and strip and strips and wire. We expect combinatorial backgrounds to be totally negligible with a large safety factor.

Background was supposed to be the make-or-break issue. The very slow drift time of the NITPC integrates over the whole train. This is not a disadvantage at the NLC, compared with a e-TPC, because both TPCs integrate over the train. At TESLA, however, there is a difference of a factor of 19 between the integrated flux of the NITPC and that of a e-TPC. This factor is mitigated by the lower gas density (Table 2, factor of 2), and also by two other smaller factors, leaving a total factor of 6. Table 2 also shows that the NITPC at 6T (Silicon Detector option) has a lower background rate than the e-TPC (Large Detector option), while having approximately the same momentum resolution (cfr. with Fig. 2 below). Still, a typical NITPC event raw size was 1GByte for TESLA.

The detector underwent a full GEANT4 simulation, using the chamber parameters of Table 2. The backgrounds were simulated using the programs available at[5], and the NLC photon rate was multiplied by 6.0 to obtain the TESLA photon rate.

Parameter	Value	Comment
Electron capture cross section	80 MBarn	-
v_d(E=0.2 kV/cm)	430 cm/sec	
v_d(E=0.4 kV/cm)	860 cm/sec	
v_d(E=0.8 kV/cm)	1500 cm/sec	mobility decreasing toward saturation
Diffusion, $\sigma_l \sim \sigma_t$	0.07mm$\sqrt{L(cm)/E(kV/cm)}$	
Negative Ion stripping mean free path	$\sim 10\mu m$	At $100\mu m$ from wire center
Gain	7700	Sense wire voltage (SWV) 2730 V
Gain	20000	SWV 2750V, He/CS_2 83/17, P=0.92 Atm
Gain	4500	GEM at 580V, He/CS_2 83/17

Table 1: He/CS_2 80/20 parameters measured in a mini-NITPC with 9 mm pitch and 5 mm gap in endcap MWPC. From dE/dx to avalanche, we list electron capture probability, drift velocity and diffusion, ion stripping probability, and gain.

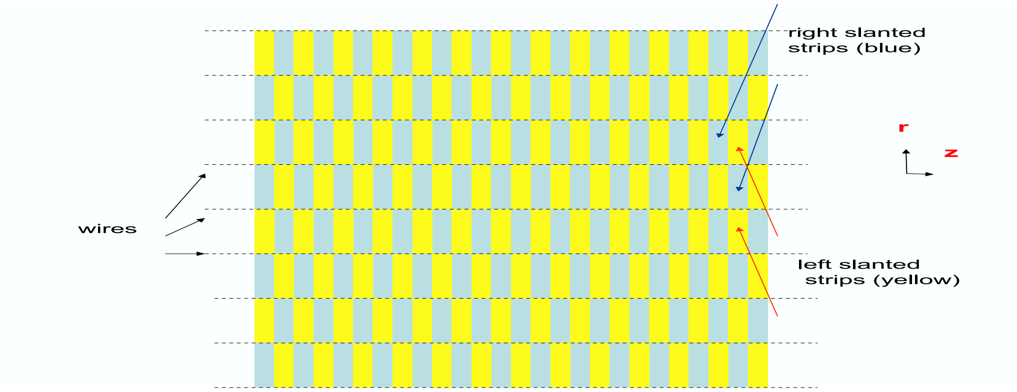

Figure 1: The detector surface layout scheme. The wires are strung vertically, and readout pads are daisy-chained to form strips. Black pads are chained along the NE-SW diagonals, and white pads are daisy-chained along the NW-SE diagonals.

A pre-filter was used to reduce data. Background events fall mostly in two categories, single "dots" of ionization (expanded by diffusion) and longer electron tracks nearly along the $z-$axis. In both cases, in our geometry, they tend to illuminate a single wire, making the pattern distinguishable from a genuine track. Clusters of "good" hits were further compacted into a "macro-hit" which was the center of gravity of many hits. The reduction factors due to the pre-filter are summarized in Table 3.

With the backgrounds under control, one should be concerned with space charge effects. We note that this detector has not only a lower ionization density, but also a capacitance 12.5 times larger than the e-TPC (Table 2). Under all the background scenarios considered in Table 2, and assuming similar detector planes, the NITPC will suffer less space charge effects than a e-TPC.

A Helix finder, like that of BaBar, was used in the NITPC to reconstruct the tracks. The momentum resolution is shown in Fig. 2. It is better that that of a e-TPC due to a combination of higher spatial sampling and lower longitudinal diffusion. Its average efficiency for tracks of $p_t > 0.5$ GeV and $\cos\theta < 0.8$ was 0.975. Some high-p_t tracks lying in the read-out planes are poorly reconstructed, as can be seen in figure 3. The algorithm was never improved to account for these tracks, though it can be at a further stage of development. Excluding those tracks, efficiency becomes as high as 0.995.

Concluding, we would like to also point out a negative issue that needs to be addressed. There is no time information about the tracks, from the NITPC itself. The NITPC would need the information from outside devices to address this problem. These include the vertex detector, the calorimeter, and also a possible Scintillating Fiber system located between tracker and calorimeter. Such a system is part of the current LC R&D program. More simulation will have to be undertaken to fully address this point.

FY2004 Project Activities and Deliverables

With most of the simulation behind us, we wish to concentrate on building a viable prototype to show that the resolution and background tolerance are as advertised. In year 1, we will make some preliminary tests of other known electronegative gases, and measure the ageing properties of electronegative gas mixtures. We will advance the simulation on issues of timing resolution, and improve the tracking near or inside the detector planes of the azimuthal NITPC. We will also design a prototype for test beam purposes.

FY2005-2006 Project Activities and Deliverables

In year 2 and 3 we will build and operate a 30X30X30 cm^3 prototype. There are several important goals here. What is the optimal working point of the chamber? We need to extract the CS_2 concentration, gain and drift voltages, and FADC rate. Given the working point, what is the ultimate tracking resolution? By using a X-ray tube, we will also probe tracking in a high background (a very important test), space charge effects (also an important test), and probe possible ageing effects.

Budget justification

The design, building and operation of a one cubic foot module will require 1/4 of a postdoc, one graduate student, and undergraduate help. We assume that we will not buy all the needed electronics, to reduce costs, and will use a multiplexing scheme to read the whole chamber. Parts of the device will be built in the WSU machine shop.

Three-year budget, in then-year K$: Temple University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	13.000	13.000	26.000
Graduate Students	18.000	19.000	20.000	57.000
Undergraduate Students	8.000	8.000	8.000	24.000
Total Salaries and Wages	26.000	40.000	41.000	107.000
Fringe Benefits	6.000	7.000	7.000	20.000
Total Salaries, Wages and Fringe Benefits	32.000	47.000	48.000	127.000
Equipment	0	5.000	7.000	12.000
Travel	2.000	2.000	2.000	6.000
Materials and Supplies	1.000	1.000	1.000	3.000
Other direct costs	0	0	0	0
Total direct costs	35.000	55.000	58.000	148.000
Indirect costs	17.500	27.500	29.000	74.000
Total direct and indirect costs	52.500	82.500	87.000	222.000

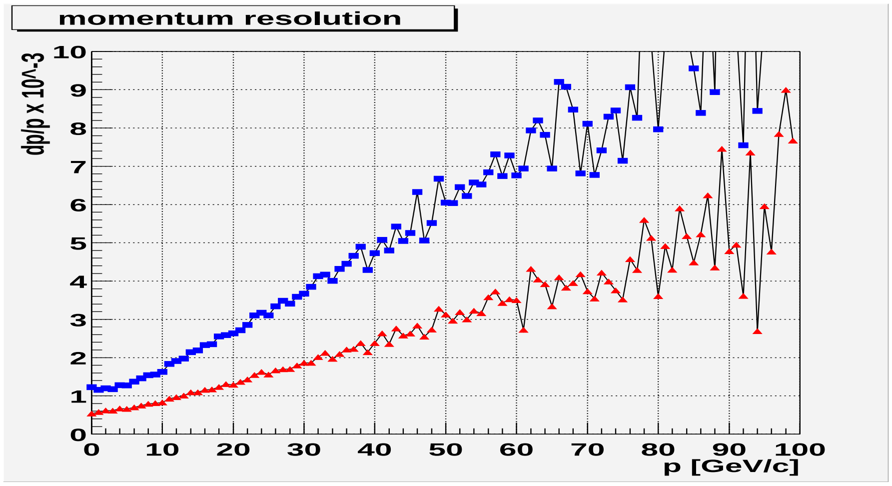

Figure 2: Momentum resolution versus momentum, as produced by our simulation, for the e-TPC and the NITPC. Red triangles: NITPC. Blue squares: e-TPC.

Three-year budget, in then-year K$: Wayne State University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	2.000	2.000	2.000	6.000
Total Salaries and Wages	2.000	2.000	2.000	6.000
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	2.000	2.000	2.000	6.000
Equipment	0	0	0	0
Travel	3.000	3.000	3.000	9.000
Materials and Supplies	5.000	5.000	5.000	15.000
Subcontract (Temple)	52.500	82.500	87.000	222.000
Other direct costs	0	0	0	0
Total direct costs	62.500	92.500	97.000	252.000
Indirect costs	5.100	5.100	5.100	15.300
Subcontract Indirect costs	12.750	0	0	12.750
Total Indirect costs	17.850	5.100	5.100	28.050
Total direct and indirect costs	80.350	97.600	102.100	280.050

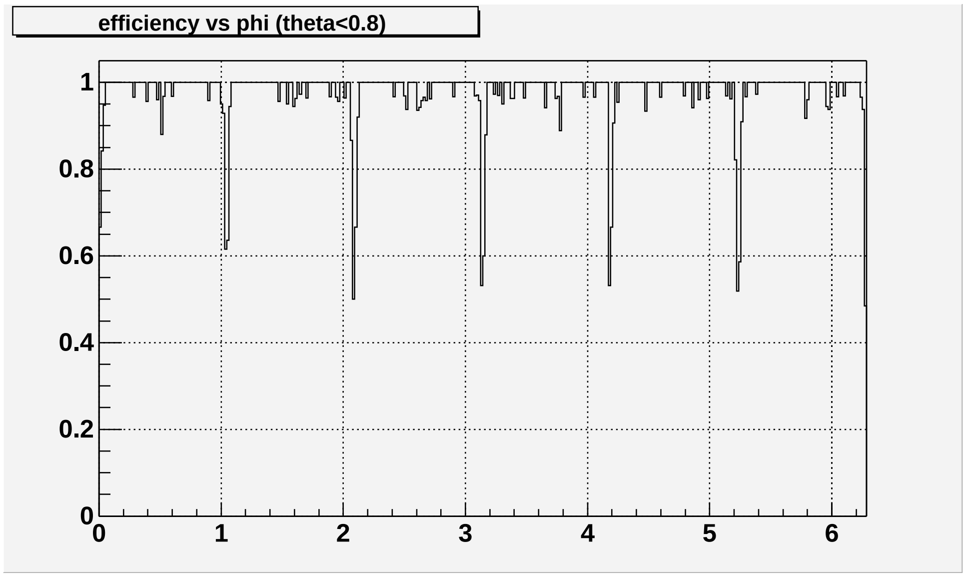

Figure 3: Helix finder efficiency vs. ϕ. The ϕ points of low efficiency coincide with those of read-out planes.

Parameter	e-TPC	NITPC	Comment
Mag. Field	3T	3T	
average drift dist.	1.35 m	0.33 m	
N of samples/track	100	10^4	N_e for NITPC
N of el./sample	200	1	
transv. diffusion, $\langle\sigma_t\rangle(\mu$m)	680	400	$\langle\sigma_t\rangle = (2/3)\sigma_{max}$
long. diffusion, $\langle\sigma_l\rangle(\mu$m)	$\gg 680$	400	accounting drift distance
TPC surface charge (nC)	0.4	5	space charge distortion par.
TPC cage	N/A	N/A	thicker in NITPC
Detector membranes	0	0.5% X_0	for perp. tracks
Endcap material	N/A	0.5% X_0	No endcaps in NITPC
NLC background density (a.u.)	1	0.5	LD, lighter gas mixture
TESLA background density (a.u.)	0.05	0.3	LD
NLC background density (a.u.)	1	0.05	Small Detector, 6T
TESLA background density (a.u.)	0.05	0.03	Small Detector, 6T

Table 2: A comparison of parameters of a state-of-the art e-TPC[4] and a preliminary design for the NITPC. For the purpose of comparison, an azimuthal NITPC is considered with 6×2 segments. For the last two rows, the comparison is between a LD e-TPC and a SD NITPC.

performance parameter	value
background suppression factor	20
data reduction factor after clusterization	1000
efficiency for signal	0.92
output number of hits	7×10^4
S/B	0.2

Table 3: Data reduction software performance.

References

[1] D.P. Snowden-Ifft, C. J. Martoff and J.M. Burwell, Phys.Rev.D61:101301,2000

[2] C.J. Martoff *et al.*, Nucl.Instrum.Meth.A440:355-359,2000; T. Ohnuki, D. P. Snowden-Ifft and C.J. Martoff, Nucl.Instrum.Meth.A463:142-148,2001.

[3] A. Schreiner, Tracking Group Talk, NLC Meeting, Cornell Univ., July 2003; `http://motor1.physics.wayne.edu/~schrein/science/nitpc.htm`

[4] D. Karlen, Tracking Group Talk, NLC Meeting, Cornell Univ., July 2003; R. Settles, ibid.

[5] `http://www.slac.stanford.edu/accel/nlc/local/systems/beamdelivery/geant/LD/`

4.3 Straw Tube Wire Chambers for Forward Tracking in the Linear Collider Detector

Personnel and Institution(s) requesting funding

O. K. Baker, Hampton University K. McFarlane, Hampton University V. Vassilakopoulos, Hampton University T. Shin, Hampton University

Collaborators

Hampton University: O.K. Baker, K. McFarlane, V. Vassilakopoulos, T. Shin

Other HBCU's and personnel will be added as part of the Center for the Study of the Origin and Structure of Matter (COSM), a NSF-funded Physics Frontiers Center.

Project Leader

O. Keith Baker
baker@jlab.org
757-727-5820

Project Overview Hampton University proposes to perform research and development of a straw-tube based wire chamber for charged particle tracking in the Linear Collider Detector. One proposed detector layout would use straw tubes for forward tracking at large radii. Such a layout is necessary (forward tracking) in order to ensure hermiticity and for luminosity measurement. The Forward Chamber (FCH) would extend radially from the Time Projection Chamber inner radius to just below the outer radius of a suggested Time Projection Chamber (TPC) field cage. There would be several layers of straw tubes with several different wire orientations, including stereo wires.

Hampton University, a member of the ATLAS Collaboration at the LHC, is part of the US group constructing the barrel Transition Radiation Tracker (TRT) for the Inner Detector. The TRT is a straw-tube based gaseous wire chamber capable of handling event rates as high as 18 MHz per 0.75-meter long (half-) straw. This system will be a charged particle tracking device as well as a particle identification detector, especially for electron-hadron separation. There will be strong overlap and synergy between the current LHC activity and the proposed NLC research and development. The tools and techniques used in one case will benefit the other. The Hampton University group will continue to work on LHC detectors and simulations during the time of this NLC activity.

Hampton University proposes to apply the experience and technical knowledge gained from this project to the tracking working group of the Liner Collider community. We will extend the work done for the LHC detector to tracking in the forward direction where the TPC and the LC vertex detectors performance would either not exist or be degraded compared to the central region. The use of CF_4 gas in tracking chambers serves two purposes: (1) It is a fast gas, that is the charged particle drift velocity in a gaseous mixture containg this compound is approximately 100 μm/ns. Fast gas recovery times in tracking chambers means higher rates can be handled. (2) It acts as a cleaning agent under certain conditions. Chambers may be effectively regenerated by flushing with a mixture including CF_4 without having to physically remove the chamber to clean it of silicon deposits (silicon deposits on wires degrade the chamber performance over time in a high rate environment).

In contrast to the benefits, there can be rather severe ageing effects on chambers that use CF_4 in a high rate environment; this has been seen in our development of LHC wire chambers. Recognizing that the LC charged particle event rate will be a small fraction of that expected (and planned for) at the LHC, there are still several outstanding tracking issues that need to be addressed for gaseous detectors. The Hampton group proposes to study the following issues for LC tracking:

FY2004 Project Activities and Deliverables

1. The effect of CF_4 gas on detector components in the LC environment. These components include (i) gold-plated tungsten wire, (ii) straw walls, and (iii) electronics boards that come into contact with this gas This will have two phases. In Phase One (FY2004) we will bring the proposed system (gas, irradiation, electronics, DAQ, test chamber) into operation and get results from short-term tests. We will build a gas system capable of handling a two or three component mixture. The group will also deliver a report on our experience (from ATLAS TRT development) with CF_4 in a high radiation environment. Although the rates at the LC will be lower than at the LHC, the work should be useful to this collaboration for long term stability and efficiency issues for the LC.

2. The use of thin-walled straw-tube wire chambers for charged particle tracking, including an analysis of the requirements on a drift tube system for forward tracking. This would include estimates of occupancy, and ionization current. Additionally, we will build and test a small straw-tube wire chamber to be used with this gas system. It is expected that this work will carry over into the next fiscal year. In order to carry out this work, the Hampton group proposes to build an irradiation system providing high ionization currents, since the deleterious effects from CF_4 show up only when high ionization is present. The straw tube wire chambers that Hampton is helping to build for the LHC can handle rates in excess of 10 MHz per one meter long straw. An X-ray system capable of providing this ionization current will be purchased and assembled if funding levels permit it. (The reason for high ionization is so that a 10-year or so LC run could be simulated in a six-month test run, for example.)

3. Detector simulations of forward charged particle tracking at the LC. The code will be a modification of the LHC detector simulation software.

FY2005 Project Activities and Deliverables

1. Improved tracking algorithms for LC events. We will improve upon code already being used for tracking using straw-tube based gaseous detectors.

2. Phase Two (FY2005) referenced above will be implemented. We will complete long-term testing of the gas system and components under irradiation and report on the results. This activity will make use of the Hampton University experience with the ATLAS TRT straw-tube modules.

FY2006 Project Activities and Deliverables

1. Define an initial detector geometry for a straw tube forward tracker;

2. Continue detector simulations of charged particle tracking at the LC. The code will be a modification of the LHC detector simulation software. LC tracking code based upon the initial forward tracker design that can be used in physics studies will be developed.

Budget justification

In order to carry out this research and development program, we request funds to partially support a single postdoctoral researcher for years FY005 and FY006. The postdoc will use facilities on the Hampton University campus, in conjunction with the group of PhD-level researchers and students already in the LHC group. There is no request for funds during the first year of the work, except for a small amount to go towards equipment (standard laboratory equipment such as multimeter, scope probe, etc). All other funds will be paid from COSM for the first year. The requested budget for a three year period is shown below in thousands of US dollars:

The postdoctoral researcher will assist with detector research and development, detector simulation, and code development for straw tube wire chamber tracking. There will be two undergraduate student workers for the duration of the research and development project. Student support for this project will come from the Hampton University Center for the Study of the Origin and Structure of Matter (COSM).

The indirect cost is 49% of all items shown, except for equipment.

Three-year budget, in then-year K$: Hampton University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	50.000	52.500	102.500
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	50.000	52.500	102.500
Fringe Benefits	0	9.200	9.700	18.900
Total Salaries, Wages and Fringe Benefits	0	59.200	62.200	121.400
Equipment	5.000	0	0	5.000
Travel	0	0	0	0
Materials and Supplies	0.0	5.000	5.000	10.000
Other direct costs	0	0	0	0
Total direct costs	5.000	64.200	67.200	136.400
Indirect costs	0	31.137	32.592	63.729
Total direct and indirect costs	5.000	95.337	99.792	200.129

4.4 R&D towards a Silicon drift detector based main tracker for the NLC-SD option

Personnel and Institution(s) requesting funding

Rene Bellwied, David Cinabro, Vladimir Rykov, Wayne State University

Collaborators

David Lissauer, Francesco Lanni, Vivek Jain, Brookhaven Physics Department

Veljko Radeka, Zheng Li, Wei Chen, Brookhaven Instrumentation Division

Project Leader

Rene Bellwied
bellwied@physics.wayne.edu
313-577-5407

Project Overview

During the past three years our group was partially funded by Fermilab Director's funds and the NSF, in order to develop a scheme in which Silicon drift detectors could be used for the main tracking device in the NLC-SD option. We participated in the design study which led to the SD layout as described in the Snowmass Resource Book. Our main effort during the past three years was two-fold:

a.) to perform simulations that show the physics capabilities of a Silicon based main tracker and compare its performance to the gaseous tracker as proposed for the L-detector option.

b.) to further develop the necessary hardware in terms of the wafers themselves, the mechanical support structure and the front-end/readout electronics based on our original design for the STAR-SVT at RHIC

With respect to a.) Vladimir Rykov has worked with us for the 18 months on simulations and software development and is now employed by RIKEN in Japan. His work's main emphasis was on comparative performance simulations in the existing software framework and a study of the track timing performance of SDD's which can be used in order to distinguish between pile-up events in the detector.Preliminary results show that the tracking efficiency, hit resolution, two-track resolution and momentum resolution obtained with a silicon drift tracker is equivalent or superior to the gaseous tracker option.

With respect to b.) Rene Bellwied and David Cinabro have mostly worked on a new detector layout for the SD main tracker based on the successful STAR Silicon Vertex Tracker, which was constructed and is operated under the leadership of Rene Bellwied. Based on these past projects we propose the following steps for the future:

FY2004 Project Activities and Deliverables

We propose to continue our comparative study of the performance of a main tracker based on Silicon drift detectors. We believe that the existing tracking and pattern recognition code, originally developed for the Large detector (LD) TPC option, can be optimized and used for the 3d SD option. First encouraging results were shown at the Chicago, Santa Cruz, Arlington, and Cornell LC meetings, and can be found on our web-page. We have incorporated the proposed detector layout into the GEANT4 framework and we also intend to port a detector response code from STAR into the LC simulation framework. Finally we would like to adapt a code recently written by a WSU led software group for

STAR which allows track matching between the two main tracking detectors in STAR and the electromagnetic calorimeter in STAR. We believe that this integrated tracking code (IT) can be applied to the SD design in order to simultaneously analyze the information from the vertex detector, the main tracker and the calorimeter in order to optimize and test the energy flow paradigm.

Regarding hardware we propose to layout a first LC specific wafer design in collaboration with the BNL Instrumentation division. In the second half of the year we will submit a prototype design for production to the BNL production lab. Proposed initial changes to the existing SDD design will include:

a.) increase the detector size by using six inch rather than four inch wafers

b.) operate wafers at higher voltage (up to 2500 V) in order to accommodate longer drift length

The first year deliverable would be a version of the LC tracking code fully optimized for an SD style detector and a design and prototype of a LC specific wafer layout

FY2005 Project Activities and Deliverables

We intend to continue our simulation activity and add a testing component to the ongoing hardware effort in order to produce a next generation of Silicon drift detectors. The testing will be performed at WSU and BNL with the postdoc funded through this proposal and graduates students funded by WSU. We propose to further optimize the design and produce a larger prototype batch ($\sim$20) of new Silicon drift detectors. The new iteration will address issues based on the following improvements:

a.) increase the readout pitch in order to reduce the channel count

b.) thin the wafer from 300 microns to 150 microns

The second year deliverables would be a new integrated tracking code for the SD detector option (ITSD) and a second iteration on the LC specific Silicon drift detector prototypes.

FY2006 Project Activities and Deliverables

Our simulation effort and production of prototype improved detectors will continue. In collaboration with the Instrumentation division at Brookhaven National Laboratory we propose to design and produce a new prototype of a CMOS based front-end chip. The major changes compared to the old STAR design are:

a.) use deep sub-micron technology to improve radiation hardness

b.) reduce power consumption to allow air-cooling of the detector

c.) potentially include the ADC stage into the PASA/SCA design

d.) test tape automated bonding of the front-end to the detector rather than wire-bonding

We also propose to begin a design for the mechanical support of the Silicon ladders based on a design used for the Silicon Strip detector layer in STAR.

The third year deliverables would be a final set of prototype detectors, some prototype front-end chips, a conceptual design of a Silicon drift detector main tracker for an LC SD style detector (including support structure and electronics integration), and simulation and reconstruction code for it.

Budget justification

Throughout the three years the budget contains a sub-contract allocation in order to purchase specific component orders produced by the BNL Instrumentation division. For some of these orders the initial materials and supplies will be provided by WSU, and those items are listed under the appropriate category. The collaboration with the BNL Physics department is not supported through this proposal. BNL Physics provides manpower to the simulation and testing effort without financial support from this grant. The WSU overhead rate is 51% for onsite manpower, material and supplies and the first 25 K of a multi-year subcontract (i.e. the contract provision for BNL).

The first year budget emphasises the continuation of our simulation and reconstruction effort. Continuing salary for 50% of a postdoctoral fellow and some travel money is requested. We also initiate the subcontract with BNL for the development of a new wafer layout and electronics design.

In the second year the software and testing effort is increased by raising the postdoc contribution from 50% to 100%. In addition money is required for the purchase of Silicon starting material ($25K) at WSU, continuing mask design ($10K) and the production of a large batch of prototype detectors ($40K) at BNL. More travel money is requested for trips between BNL and WSU related to prototype production and testing as well as participation in LC workshops.

In the third year the software effort continues and additional funding is required for a second round of mask design ($10K), production of the final batch of prototype detectors ($30K), and design and production of prototype front-end chips ($50K) at BNL . More travel money is requested for trips related to prototype production and testing.

Three-year budget, in then-year K$: Wayne State University

Item	FY2004	FY2005	FY2006	Total
Other Professionals	21.018	42.037	44.462	107.517
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	21.018	42.037	44.462	107.517
Fringe Benefits (23.7%)	4.982	9.963	10.538	25.483
Total Salaries, Wages and Fringe Benefits	26.000	52.000	55.000	133.000
Equipment	0	0	0	0
Travel	4.033	6.221	10.168	20.442
Materials and Supplies	0	25.000	10.000	35.000
Subcontracts (BNL)	25.000	50.000	90.000	165.000
Total direct costs	55.033	133.221	165.168	353.422
Indirect cost	15.317	42.443	38.336	96.096
Indirect cost on Subcontract	12.750	0	0	12.750
Total Indirect costs	28.067	42.443	38.336	108.846
Total direct and indirect costs	83.100	175.664	203.504	462.268

Three-year budget, in then-year K$: Brookhaven National Laboratory

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	4.556	9.112	13.668
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	4.556	9.112	13.668
Fringe Benefits (38%)	0	1.763	3.526	5.289
Total Salaries, Wages and Fringe Benefits	00	6.319	12.638	18.957
Indirect cost on Salaries	0	3.679	7.361	11.040
Equipment	0	0	0	0
Travel	3.302	3.301	6.603	12.906
Materials and Supplies	6.603	9.905	9.905	26.413
Other	6.603	13.207	29.715	49.525
Total Equipment, Materials, Travel, and Other	16.508	23.112	39.620	75.938
Indirect Cost on Equipment etc.	8.492	13.589	23.778	45.859
Total direct costs	16.508	32.732	58.861	107.801
Indirect costs	8.492	17.268	31.139	56.899
Total direct and indirect costs	25.000	50.000	90.000	165.000

4.5 Tracker simulation studies and alignment system R&D

Personnel and Institution(s) requesting funding

T. Blass, J. Deibel, S. Nyberg, K. Riles, H. Yang, Physics Department, University of Michigan

Project Leader

K. Riles
kriles@umich.edu
(734) 764-4652

Project Overview

Introduction

The University of Michigan group has a long-term interest in helping design and construct the central tracking system for a linear collider detector. This interest is driven not by a particular favorite technology, but by the critical importance of charged-particle tracking to the physics processes we wish to investigate, which include Higgs production and decay, along with certain supersymmetric channels.

Results of Prior Research

We have contributed extensively to linear collider simulation studies, both in technical tracking reconstruction issues and in evaluating physics analysis demands upon tracker performance. Riles has served as a co-convener of the linear collider central tracking working group since 1998, sharing leadership responsibilities in different years with Dean Karlen, John Jaros and Bruce Schumm. Riles has shared responsibility for organizing working group meetings, evaluating baseline tracker designs, coordinating tracking simulations, creating & maintaining the group web site, and assembling annual joint R&D proposals.

As part of the baseline tracker design optimization, Riles wrote a stand-alone Monte Carlo hit generator and 3-d helical track fitter to study the effects of multiple scattering on particle momentum resolution *vs* momentum and *vs* polar angle for various tracker configurations. This work served as an independent cross check of the resolution studies carried out by Bruce Schumm using an analytic Billoir approach.

Yang began linear collider studies in fall 2000. He has been carrying out several related studies: 1) Studies of Higgs and Supersymmetry physics capability and 2) influence of central tracking performance on Higgs and Supersymmetry physics. As a member of the Higgs working group, he has evaluated the precision with which the Higgs mass and cross section can be evaluated at 350 GeV and 500 GeV center of mass energies. This study has used both the JAS fast Monte Carlo and the full simulation packages. Yang has independently confirmed and improved upon preliminary findings by European groups with the use of a more sophisticated and powerful fitting technique, based on Monte Carlo event interpolation. In parallel, Yang has examined the influence of central tracker parameters on the Higgs mass precision. In addition, he has assisted the SLAC simulations group in comparing the tracker's performance in full Monte Carlo simulations *vs* performance in parametrized fast Monte Carlo simulations. He has given numerous presentations on Higgs physics, Supersymmetry and tracking at various linear collider workshops[1, 2, 3, 4, 5, 6, 7] and at the Snowmass 2001 meeting[8, 9]. Yang's studies of the Higgsstrahlung process are complete and find that current baseline tracker designs in the U.S. are close to where improved resolution does not yield comparable improvement in

Higgs mass resolution, because of expected intrinsic beam energy spread in present accelerator designs. His more recent work on slepton and neutralinos[7] indicates that in some regions of sparticle mass parameter space, measuring lepton spectrum end-points to determine sparticle masses is less sensitive than was previously believed to degraded momentum resolution[10].

Research Plan

Simulation Studies

In the coming years we wish to extend the ongoing slepton/neutralino studies to additional Supersymmetry final states to understand quantitatively whether they impose more or less stringent requirements than Higgsstrahlung on tracking resolution. In particular, we will begin by exploring a larger parameter space in sparticle masses in the slepton production channel. The sharpness of the spectral end-points will be governed in part by track resolution. We wish to quantify the influence of tracking resolution on sparticle mass resolution. We expect there to be two distinct regions of importance: 1) high-momentum end-points where the same effects seen in our Higgs analysis are expected to be important; and 2) low-momentum end-points where multiple scattering may prove important.

One of the outstanding issues in comparing a gaseous central tracker to a silicon system is the importance of the greater material burden in the silicon design to low-momentum track resolution. It has been suggested by members of the linear collider supersymmetry working group that for significant regions of supersymmetry parameter space, momentum resolution in the 1-10 GeV range will limit the precision with which supersymmetry particle masses can be determined. If true, then the desire for precise sparticle mass determination may well govern the choice of barrel tracker technology. We wish to explore this possibility more quantitatively, taking into account other known sources of sparticle mass resolution degradation. The University of Colorado group led by U. Nauenberg has carried out a series of studies of slepton final states for the linear collider supersymmetry group, including studies of sparticle mass determinations. We have coordinated with the Colorado group in extending their existing analyses to address tracking performance requirements quantitatively. In addition, we will continue contributing to the tracking infrastructure development, where we have taken responsibility for more sophisticated hit merging and for evaluation of track reconstruction performance.

Alignment System

We also wish to carry out R&D on precise alignment of the linear collider tracking subsystems. The unprecedented excellent track momentum resolutions contemplated for a linear collider detector will demand minimizing systematic uncertainties in subdetector relative alignments. At the same time, for reasons discussed above, there is a strong desire for a very low material tracking system. In the case of a silicon main tracker and in the case of silicon forward disks (envisioned in all linear collider detector designs now on the table), the low material budget may lead to a structure that is far from rigid. The short time scales on which alignment can change (e.g., from beam-driven temperature fluctuations) probably preclude reliance on traditional alignment schemes based on detected tracks, where it is assumed the alignment drifts slowly, if at all, during the time required to accumulate sufficient statistics. A system that can monitor alignment drifts “in real time” would be highly desirable in any precise tracker and probably essential to an aggressive, low-material silicon tracker. The tradeoff one would make in the future between low material budget and rigidity will depend critically upon what a feasible alignment system permits.

We propose to investigate the capability of existing precise alignment schemes and to develop a system customized to the needs of a linear collider detector. Two natural candidate schemes to explore include the Rasnik alignment system implemented for the CDF detector and the Frequency Scanned Interferometer (FSI) system being developed for the ATLAS detector[11]. Both are designed to achieve 1-D or 2-D point resolutions of order 1 micron, which should be adequate for a linear collider tracking system. The Rasnik system is based on many CCD cameras trained on 2-D images whose positions are sensitive to relative misalignments. The FSI system is based on multiple interferometers fed by optical fibers from the same laser source, where the laser frequency is scanned and fringes counted to obtain a set of absolute lengths. Given the desire for low material burden in a silicon tracker, it's not clear that either system in its present design will be appropriate for a linear collider detector, although the FSI method seems more promising in that respect and is the one we will at least initially focus upon. As an active member of the LIGO Experiment since 1997 and leader of the LIGO Scientific Collaboration's Detector Characterization Working Group, Riles has acquired expertise in precise interferometry, including beam modulation techniques that may usefully enhance the FSI method. As part of our R&D effort, we would explore these and perhaps other alternative methods of optical metrology.

It should be noted that the methods developed for central and forward tracker alignment may also prove useful for a vertex detector, where again, there is a strong desire for thin detector material that may be subject to short-term position fluctuations. Similarly, the methods developed here may prove useful for alignment monitoring of accelerator components far upstream of the detector (e.g., in the main linacs). Given the natural wide distribution of accelerator components *vs* a relatively compact tracker system, however, it's not clear that a tracker solution will be cost effective for the accelerator. In any case, we will stay cognizant of vertex detector and accelerator needs and explore these possibilities, as the tracking alignment system design evolves.

We have begun work on this alignment R&D using funds from other sources and have given a preliminary report[12]. We have purchased many of the main elements of a bench demonstration system, including a dedicated optical table, the tunable laser, several high-bandwidth photodiodes, a spectrum analyzer, and a variety of optical components, including a Faraday isolator. At present, two undergraduates (Blass, Nyberg) and a half-time graduate student (Deibel) work on this project, under the supervision of Yang and Riles.

FY2004 Project Activities and Deliverables

During the first year we will carry out simulation studies of the tracking performance requirements imposed by measurements of slepton production, specifically imposed by desired precision on sparticle masses. We will write a detailed technical report on our findings in which the gaseous and silicon tracker designs are compared quantitatively.

We will also continue out newly started program of alignment R&D. Specifically, we will finish acquiring the components for and building a demonstration-level frequency-scanned interferometer on an optical bench. In parallel, we will come up with a conceptual design of an alignment scheme for the American baseline silicon barrel tracker and the silicon forward disk trackers and write a general simulation program that allows the performance evaluation of various schemes. It is envisioned that hundreds of absolute length measurements between pairs of reference points would be used in a global fit to determine the local and global alignment parameters of the tracking subsystems. A detailed progress report on this effort will be delivered at the winter 2004 American linear collider physics group meeting.

FY2005 Project Activities and Deliverables

Simulation studies in the second year will depend on findings from the first year on slepton production. We expect, however, to investigate other supersymmetry channels involving isolated leptons whose precise measurement imposes stringent performance requirements on the tracker. Chargino production is a natural channel to investigate. We will deliver a technical report on our findings.

Using the FSI infrastructure put together in the first year, we will carry out measurements on the bench of performance and explore modifications to improve absolute precision, robustness, and measurement speed. A technical report will be written on our findings.

FY2006 Project Activities and Deliverables

We anticipate that our supersymmetry/tracking simulation studies will have been completed to satisfaction by the start of the third year, but depending on what has been learned, we may wish to pursue certain specific topics in further detail. If so, another technical report will be written on our findings.

We hope by the start of the third year to have a concrete design in hand for a full alignment system and to have evaluated singly the primary issues affecting that design. At that point we would wish to build a partial prototype of the system to test system integration issues, including miniaturization of the components tested previously on the optical bench. We expect to continue deferring the purchase of a commercial laser with the frequency tuning range, stability and intensity envisioned for the final system. If such a laser is indeed needed to satisfactorily address outstanding R&D issues, however, we would expect to request a grant supplement when the time comes. We do not request funding for its purchase here.

Budget justification

In the first year, we request funding here for a half-time graduate student, for employment of two undergraduates, for the purchase of the remaining components needed to build a bench-level frequency scanned interferometer, and for travel to biannual linear collider meetings.

In the second year, we request funding for a half-time postdoctoral fellow, for two half-time graduate students, for employment of undergraduates, for additional optical equipment to enhance the frequency scanned interferometer, and for travel.

In the third year, we request funding for a quarter-time technician, a half-time postdoctoral fellow, for two half-time graduate students, for employment of undergraduates, for components of a partial alignment system prototype, and for travel.

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

Item	FY2004	FY2005	FY2006	Total
Postdoctoral Fellow	0	21.000	22.000	43.000
Other Professionals	0	0	15.000	15.000
Graduate Students	6.900	14.352	14.950	36.202
Undergraduate Students	8.000	6.000	4.000	18.000
Total Salaries and Wages	14.900	41.352	55.950	112.202
Fringe Benefits (@28%)	4.172	11.578	15.666	31.416
Total Salaries, Wages and Fringe Benefits	19.072	52.930	71.616	143.618
Equipment	10.000	5.000	25.000	40.000
Travel	3.000	3.000	3.000	9.000
Materials and Supplies	0	0	0	0
Other direct costs (tuition)	6.200	13.144	13.950	33.294
Total direct costs	38.272	74.074	113.566	225.912
Indirect costs (@53%,excl. tuition/equipment)	11.698	29.643	39.422	80.763
Total direct and indirect costs	49.970	103.717	152.988	306.675

References

[1] "Measurement of Higgs Mass at NLC", H. Yang, Presentation at Workshop on Higgs Physics at a Linear Collider, University of California, Davis, January 27-28, 2001, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/nlc-higgs.ps.gz`.

[2] "Measurement of Higgs Mass and Cross Section at NLC", H. Yang and K. Riles, Presentation at Workshop on Future e^+e^- Linear Colliders, Johns Hopkins University, March 19-21, 2001, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/higgs-mass-xs.ps.gz`.

[3] "Impact of Tracker Design on Higgs Mass Resolution", H. Yang and K. Riles, Presentation at Workshop on Future e^+e^- Linear Colliders, Johns Hopkins University, March 19-21, 2001, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/trackres-jhu.ps.gz`.

[4] "A First Look at Track Reconstruction with High Random Backgrounds", H. Yang and K. Riles, Presentation at American Linear Collider Workshop, University of Chicago, January 7-9, 2002, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/trackeff.pdf`.

[5] "Measurement of Higgs Mass and Cross Section at NLC" H. Yang and K. Riles, Presentation at Santa Cruz Linear Collider Retreat, June 27-29, 2002, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/higgs-ucsc.pdf`.

[6] "Impact of Tracker Design on Higgs Mass Resolution and Cross Section", H. Yang and K. Riles, Presentation at Santa Cruz Linear Collider Retreat, June 27-29, 2002, `http://tenaya.physics.lsa.umich.edu/$\sim$hyang/talks/trackres-ucsc.pdf`; see updated report at `http://tenaya.physics.lsa.umich.edu/~keithr/LC/HiggsTrackSummer2002.pdf`.

[7] "Search for Neutralino and Smuon", H. Yang and K. Riles, Presentation at American Linear Collider Workshop, University of Texas, Arlington, January 9-11, 2003, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/smuon-uta.pdf`.

[8] “Measurement of Higgs Mass and Cross Section at a Linear Collider”, H. Yang and K. Riles, P112 in *Proceedings of Snowmass 2001*, Snowmass Village, Colorado, June 30 – July 21, 2001, ed. Norman Graf, SLAC-R-599. Proceedings.

[9] “Impact of Tracker Design on Higgs Mass and Cross Section Resolutions”, H. Yang and K. Riles, E3040 in *Proceedings of Snowmass 2001*, Snowmass Village, Colorado, June 30 – July 21, 2001, ed. Norman Graf, SLAC-R-599. Proceedings.

[10] “Linear Collider Detector R&D”, J. Brau *et al.*, Report of International Linear Collider Detector R&D Committee, August 28, 2002, `http://blueox.uoregon.edu/~lc/randd.pdf`.

[11] “Frequency Scanned Interferometry (FSI): The Basis of a Survey System for the ATLAS ID using fast automated remote interferometry”, A.F. Fox-Murphy *et al.*, Nuc. Inst. and Meth. **A383**, 229 (1996).

[12] “Frequency Scanned Interferometer for Tracker Alignment”, Presentation at American Linear Collider Workshop, Cornell University, July 13-16, 2003, `http://tenaya.physics.lsa.umich.edu/~hyang/talks/fsi-july-14-2003.pdf`.

5 Calorimetry

5.1 Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter

Personnel and Institution(s) requesting funding

G. Blazey, D. Chakraborty, A. Dyshkant, M. Martin,
V. Rykalin, V. Zutshi.

Northern Illinois Center for Accelerator and Detector Development/
Northern Illinois University.

Mark Adams, Cecilia Gerber, Nikos Varelas.

University of Illinois at Chicago.

Collaborators

M. Oreglia et al., *University of Chicago*,

U. Nauenberg et al., *University of Colorado, Boulder*,

G. Wilson et al., *University of Kansas*,

D. Karmgard et al., *University of Notre Dame*.

Project Leader

V. Zutshi
`zutshi@fnal.gov`

(815)753-3080

Project Overview

The Northern Illinois University(NIU)/Northern Illinois Center for Accelerator and Detector Development (NICADD, `http://nicadd.niu.edu`) and the University of Illinois at Chicago (UIC) groups are interested in calorimeter R&D for the proposed Linear Collider. We propose to develop, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet energy measurement using energy-flow algorithms (EFA, see below). Software simulations/algorithm development and hardware prototyping are envisaged as the two main components of our efforts. This proposal addresses the second component while the first is the subject of a separate proposal. The end goal of this research project will be the development of reliable performance and cost estimates for scintillator-based digital hadron calorimeter options suited for, but not limited to, an e^+e^- linear collider.

It is clear that for the Linear Collider to fulfill its physics charter multi-jet final states will have to be exceptionally well measured. In particular, superior resolutions in jet (30%/$\sqrt{E}$ or better) and missing energy measurements will be critical for discovery and characterization of the new physics as well as for precision tests of the Standard Model (SM). The most promising means to achieving such unprecedented resolutions at the next linear collider is through energy flow algorithms (EFA) which require fine lateral and longitudinal segmentation of the calorimeter. We propose to conduct a comprehensive feasibility study of a finely segmented hadron calorimeter with transverse cell cross section of $\approx$6-16 cm^2 and 30-40 layers of active medium. The very large number ($\approx$ 3-5 million) of readout channels pose a significant challenge in the form of complexity and cost of signal processing and data acquisition. Reducing the dynamic range of the readout is a potential solution. At one extreme, it may be a "digital" calorimeter with a single-bit readout for each cell, with the threshold set to detect the passage of a minimum ionizing particle. Preliminary studies have indicated that with sufficiently small cells, a 1-bit digital readout may be adequate, but we propose to find the optimal balance between cost and performance in deciding on the cell size and dynamic range. For example, a 2 or 4-bit readout may improve performance without significantly adding to the cost.

Between the NIU and UIC groups, we have extensive experience in calorimeter hardware, electronics, software, and algorithm development, gained at the DØ experiment and elsewhere. The NIU/UIC team has been investigating, for more than a year now, a sampling digital hadron calorimeter with scintillator as the active medium. This option capitalizes on proven detection techniques and well known readout devices. Absence of fluids, high-voltage, and readout electronics inside the detector aids longevity and operational stability. The main challenge to a scintillator-based digital hadron calorimeter is the cost of transforming light, from such a large number of channels, to electrical signals. We plan to seek the optimal solution by evaluating different options through simulation and prototyping studies. In this task we are co-ordinating our efforts with the European calorimeter R&D especially the Tile-Cal group at DESY. This interaction takes place under the umbrella of the CALICE collaboration which bands together universities and labs, interested in developing calorimeters for the Linear Collider, on both sides of the Atlantic.

A GEANT4-based simulation package has been installed and tested on several NIU machines and is now being used to model our preliminary prototype designs. We expect the synergy between these simulations and the hardware prototyping to contribute significantly to our understanding of the scintillator based design. NIU's simulation and algorithm development efforts, detailed in the other proposal, will provide valuable input in deciding the optimum transverse and longitudinal segmentation, absorber material and detector layout.

Already, on the hardware side, hexagon-shaped prototype cells of various sizes, thicknesses and fiber groovings have been machined and are being evaluated together with fibers of different shapes, dimensions and optical treatments. This research and the work outlined below is being carried out by our faculty and staff with the help of NIU and UIC graduate students (K. Francis, I. Harnarine, S. Khan and P. Torres).

Based on our preliminary conclusions of scintillator-fiber system optimization we have constructed a 7 cell wide 12 layer deep layer stack for cosmic muon tests. The 84 channels will initially be read out with multichannel Photo-Multiplier Tubes (PMT's). Once the cell response has been characterized with PMT's, semiconductor photo-detectors will gradually replace them as the readout devices. Our interest in semiconductor photo-detectors stems from their immunity to the high magnetic fields (4-5 Tesla) being contemplated for the Linear Collider detector and the likelihood of their prices continuing to move downward. Some of the solid-state photo-detectors which we will be testing with our layer stack are Avalanche Photodiodes (APD's) and Geiger mode photo-diodes (like Si-PM's and MRS devices). These detectors can work at room temperature and offer complementary strengths with APD's having high quantum efficiency (70-80%) and moderate gains while Si-PM's have high gain (upto 10^6) but conventional photo-tube quantum efficiencies (12-15%). Pooling together the resources of their mechanical and electrical shops, NIU and UIC have already designed and fabricated an optical (fiber-sensor) interface and a PC board for reading out the APD's. In addition to the above mentioned photo-detector characterization, absorber material choice, investigation of tooling and mechanical assembly options and the use of extruded scintillator are slated for study.

All this will culminate in the exposure of our prototype (1 m^3, $\approx$30K channels) to a test-beam. A test-beam is essential not only to understand the performance and reliability of our hardware but also to validate the Monte Carlo hadronic simulations. We are co-ordinating our test-beam plans with the American and European LC calorimeter groups so that a cohesive and comprehensive R&D program, encompassing the varied calorimetry options, can be carried out.

FY2004 activities and deliverables

During the first year we will finish implementing our prototype design in a GEANT4 simulation, carry out relative and absolute light yield measurements for various scintillator cell sizes and material (for e.g. Kuraray/Bicron vs extruded). Optimum grooving, reflector treatment, and fiber size and shape will be studied. We will also characterize photo-detectors (APD's, Si-PM's, MRS etc.) in terms of performance, reliability, stability of operation and cost. The first year deliverables are a GEANT4 prototype simulation and a decision on the optimum cell-fiber-grooving-treatment configuration.

FY2005 activities and deliverables

Investigations into photo-detectors will continue. Assuming reasonable light yield from extruded samples, the NICADD extrusion line will be operated to deliver scintillator cells of the optimum shapes, sizes and groovings. The second year deliverable will be a full Linear Collider detector simulation incorporating our HCAL design, a decision on the type of photodetector we want to use for the scintillator-based HCAL, readout board design and initiation of a prototype module.

FY2006 activities and deliverables

During the third year we will complete the construction of prototype module for beam tests, collect and analyze data with it. This implies fabrication and testing of the full readout chain. A full specification of the support structure and fiber routing scheme of the HCAL will follow. This will have to be done keeping in view the evolving designs of the other subsystems of the detector so that interfacing will be a smooth operation. In addition, tooling for automated mechanical assembly will be done. The third year deliverable will be a Technical Design Report based on our test-beam experience.

Existing Infrastructure/Resources

The funds requested in this proposal will be augmented the following support, totaling more than $1M, from other sources.

NIU

(a) NICADD personnel,
(b) NICADD scintillator extruder line,

(c) Interdisciplinary collaboration with NIU Mech. Engineering Dept. on extruder die design,
(d) NIU machine shops,
(e) Collaboration with Fermilab on extruder operation,
(f) $45K Advanced Detector Research DOE grant (FY2002-03).

UIC

(a) Labs for studying optical fibers and electronics including board design,
(b) Well-equipped departmental machine and electronics shops,
(c) Computing hardware.

Budget justification

FY2004: Prototype geometry implementation inside GEANT4 and light yield measurements for different scintillator cell configurations and various photo-detectors will involve NICADD staff members (not included in the NIU budget presented here) and 1.5 FTE graduate students (1.0 NIU + 0.5 UIC). The equipment requested are a test stand for the detector elements, photodetectors, and readout electronics. Relatively small volumes of scintillators, absorbers, optical fibers, optical paints, glue, and couplers make up the materials and supplies.

FY2005: Operation of the extrusion line and design of the readout boards and mechanical assembly, for the prototype module, will be done with the additional support of a 0.5 FTE engineer (NIU) and a post-doc (0.25 FTE, UIC). Continued photodetector R&D will require equipment and material/supplies at the same level as FY2004. Support for 1.5 FTE graduate students will be maintained.

FY2006: Fabrication of the mechanical assembly and production and testing of the full readout chain for the test-beam will require continued support for an engineer(0.5 FTE, NIU) a post-doc (0.5 FTE, UIC) in FY2006. Support will be needed for an additional 0.5 FTE graduate student (NIU). This will bring the total graduate student FTE's to 2.0. Much larger amounts of materials and supplies (scintillator, fibers, optical glue, reflector material etc.) will be needed to build the prototype module. Photodetectors, readout electronics, and a data acquisition system for the tests account for the equipment request.

The travel funds (2004-2006) will cover costs of travel by group members to collaborating institutions (travel between NIU/UIC not included) and for attending conferences/meetings for the purposes of this project only. The budget takes into account the NIU (UIC) mandated fringe: 44%(28.55%), indirect cost: 26%(26%) and tuition remission: 0%(37%) rates.

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

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	40.000	42.000	82.000
Graduate Students	19.500	20.085	31.031	70.616
Undergraduate Students	0	0	0	0
Total Salaries and Wages	19.500	60.085	73.031	152.616
Fringe Benefits	0	17.600	18.480	36.080
Total Salaries, Wages and Fringe Benefits	19.500	77.685	91.511	188.696
Equipment	15.000	10.000	50.000	75.000
Travel	2.500	4.000	6.000	12.500
Materials and Supplies	7.500	7.500	40.000	55.000
Subcontracts-U.Illinois,Chicago	22.397	42.549	63.697	128.643
Total direct costs	66.897	141.734	251.208	459.839
Indirect costs (26% of non-equipment)	13.493	23.865	35.753	73.111
Total direct and indirect costs	80.390	165.599	286.961	532.950

Three-year budget, in then-year K$: University of Illinois at Chicago

Item	FY2004	FY2005	FY2006	Total
Other Professionals	0	11.000	22.660	33.660
Graduate Students (6 months)	9.100	9.370	9.650	28.120
Undergraduate Students	0	0	0	0
Total Salaries and Wages	9.100	20.370	32.310	61.780
Fringe Benefits	0	3.143	6.472	9.615
Total Salaries, Wages and Fringe Benefits	9.100	23.513	38.782	71.395
Equipment	0	0	0	0
Travel	0	1.500	1.500	3.000
Materials and Supplies	6.000	6.000	7.400	19.400
Other direct costs	3.400	3.500	3.600	10.500
Total direct costs	18.500	34.513	51.282	104.295
Indirect costs	3.926	8.063	12.397	24.386
Total direct and indirect costs	22.426	42.576	63.679	128.681

5.2 RPC Studies and Optimization of LC detector elements for physics analysis

Personnel and Institution(s) requesting funding

Ed Blucher, Mark Oreglia (University of Chicago)

Collaborators (Not receiving funding from this subaward)

Argonne National Lab, Northern Illinois University

Project Leader

Mark Oreglia
m-oreglia@uchicago.edu
(773)-702-7446

Project Overview

We are studying performance aspects of glass RPC chambers in collaboration with Jose Repond at ANL. The goals of this research are to establish the reliability and failure modes of RPCs and to design and construct a cubic-meter prototype RPC digital calorimeter for test beam evaluation late in 2005. The University of Chicago group, including Harold Sanders and Fukun Tang of our Electronics Development Group, will design some of the readout electronics for calorimeter RPC prototypes under study. Oreglia, Blucher and students will continue their studies of RPC performance in a manner complementary to what the ANL group is doing.

While much work has been done on the development of individual detector elements for LC detectors, no optimization has been performed to coordinate properties (such as granularity) amongst the tracker and EM+HAD calorimeters for physics analysis. For instance, an analysis tool receiving much attention currently is “energy flow”, an aggregate quantitity constructed from tracking and calorimetry information. Without bias towards tracking and calorimetry technologies, we propose to develop simulations of benchmark physics analyses for a variety of detector parameters. More specifically, we propose to focus on minimal Standard Model Higgs boson production (and the main backgrounds) as our physics benchmark. Using current expertise we have in studies of the ATLAS calorimeter, we intend to create energy flow, jet definition, and jet-jet mass algorithms tailored to several choices of calorimeter granularity and longitudinal segmentation; a third parameter would be the particular calorimeter material and its response to different particle types. From these studies we hope to optimise Higgs boson mass resolution and the signal-to-background sensitivity.

For the simulation work we anticipate collaborative work with NIU. In particular, NIU is helping to develop the standard ALCPG simulation package, for which we envision developing a GRID implementation. A number of institutions are expressing interest in working on “energy flow” (in addition to those mentioned already: U of Illinois at Chicago, U of Kansas, U of Texas at Arlington, U of Colorado, Boston U, U of Oregon, and SLAC). Our group at the University of Chicago is currently working on energy flow assessment and jet definition software for the ATLAS detector at the LHC, and this activity already is being conducted in collaboration with ANL. Thus, it is logical for our group to embark on such studies for the LC, and we intend to do this within the auspices of the LC calorimetry group which is coordinating the activities of the various institutions. However, it is worth noting that the project proposed in this proposal is different from energy flow development insofar as the main target of the study is to optimize the detector systems; energy flow is only one aspect of physics analysis which will be considered.

We expect to have sufficient manpower to produce significant results within the three-year period if we can bring a new postdoc on board. Blucher and Oreglia are senior personnel who will devote significant effort to the project. Other senior personnel are performing similar research for the ATLAS experiment and will contribute greatly through their instruction of students and the postdoc.

Outreach in this program will be realized through the participation of 2-6 undergraduate students, both University of Chicago students and also REU students from other universities. Every summer, the University of Chicago Physics Department supports 15-20 female and minority undergraduates to participate in physics research programs; we expect to be able to support two of these REU students in the proposed research. We will also feature RPC technology and the energy flow concept in our summer Quarknet lectures.

FY2004 Project Activities and Deliverables

In year-1 we will continue our assessment of RPC surface damage and optimization of gas mixtures. With the goal of a significant beam test in 2005, we will also design DAQ boards for a large-channel prototype RPC calorimeter which we are working on with ANL. The design work will be conducted by the EFI Electronics Shop under the direction of Harold Sanders.

FY2005 Project Activities and Deliverables

During year-2, we will also develop a simulation package based on the existing framework, but with more general treatment of the calorimeter options. Using this tool, we will generate datasets of standard physics processes. At the same time, we will be able to integrate into the detector simulations group to develop further the framework for Monte Carlo simulation of physics processes in the 2 standard detector configurations. This study will involve development of (or modification of existing) algorithms for energy flow, jet definition, and jet energy scaling suited to the Higgs boson analysis under study. We especially expect to benefit from comparisons of similar techniques under development by our group for use with the ATLAS detector at the LHC. At this point we will be able to comment on how calorimeter technologies under consideration compare to the optimization of our study. Additionally, the new EFI/ANL GRID computing team has expressed interest in creating a platform for large-scale Monte Carlo production which we intend to use for the LC studies.

In this year we will also manufacture the DAQ electronics for the beam tests of the RPC calorimeter prototypes.

FY2006 Project Activities and Deliverables

In year-3 decisions on the calorimeter technology should have been made, and we will refine the design of calorimeter electronics. We will also support development of physics analysis and the use of GRID networking for the generation of large Monte Carlo datasets.

Budget justification

The first-year budget supports one full-time equivalent undergraduate research technician (at the maximum work time allowed by the University), and salary for an additional (non-undergraduate) research technician during the summer months; the latter is likely to be a pre-matriculation graduate student, and this salary is in the “Other” category. The research technicians will assist in testing of the RPC DAQ electronics, conduct beam studies of prototype chambers, develop energy-flow analysis software for Linear Collider calorimetry, and conduct analysis of LC tracker, electromagnetic calorimeter and hadron calorimeter integrated systems with the goal of optimizing the system granularities for optimum physics analysis potential. Travel funds are requested for transport to collaboration meetings and testbeam facilities (both domestic and international). Electronics shop labor and parts for the design of one major DAQ board is also included. The “Other direct” category is for electronic shop labor.

In the followinging years the electronic shop fraction ramps down, a postdoctoral research associate is added, and the travel allowance is increased to allow for increased testbeam activity.

Fringe benefits are calculated on the postdoctoral research associate salary at rates of 20.4%, 20.9%, and 21.4% for years 1,2,3, respectively. Likewise, the summer fringe benefit rate on the student research technians is 7.7%, 8.2%, and 8.7% in years 1,2,3, respectively. Indirect costs are applied at a fixed rate of 52.5% on salaries, fringe benefits, and travel; oversight by Merle Schmitt, Director of the Division of Cost Allocations, Department of Health and Human Services, 1301 Young Street, Room 732, Dallas,TX, (214) 767-3261.

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

Item	FY2004	FY2005	FY2006	Total
Postdoc RA	0	46.125	47.278	93.403
Other Professional	4.950	4.950	4.950	14.850
Undergraduate Students	6.400	6.400	6.400	19.200
Total Salaries and Wages	11.350	57.475	58.628	127.453
Fringe Benefits	0.597	10.276	10.792	21.665
Total Salaries, Wages and Fringe Benefits	11.947	67.751	69.420	149.118
Equipment	0	0	0	0
Travel	2.500	5.000	7.500	15.000
Constructed Equipment	8.000	10.000	0	18.000
Other direct costs (Labor)	35.000	10.000	5.000	50.000
Total direct costs	57.447	92.751	81.920	232.118
Indirect costs	7.585	38.194	40.383	86.162
Total direct and indirect costs	65.032	130.945	122.303	318.280

5.3 Investigation and Design Optimization of a Compact Sampling Electro-magnetic Calorimeter with High Spatial, Timing and Energy Resolution

Personnel and Institution(s) requesting funding

Philip S. Baringer, Alice Bean, Eric Benavidez, David Z. Besson, Darius Gallagher, Carsten Hensel and Graham W. Wilson, Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045.

Collaborators

N. Graf, SLAC.

E. von Toerne, Kansas State University.

S. Bentvelsen, NIKHEF. S. Magill, Argonne.

U. Nauenberg, Colorado.

Project Leader

Graham W. Wilson
gwwilson@ku.edu
(785)-864-5231

Project Overview

Motivation: Existing linear collider (LC) detector designs emphasise precision tracking of charged particles ($\sigma(\frac{1}{p_t}) \approx 5 \times 10^{-5}\mathrm{GeV}^{-1}$) leading to fractional energy resolutions of better than 2.5% for the highest energy charged particles at a 1 TeV LC. Many of the golden physics channels have multiple heavy bosons in the final state and possibly missing energy : WW, ZH, ZH, $\mathrm{t\bar{t}}$, ZHH, $\nu\bar{\nu}$VV, chargino-pairs, etc. This leads to multi-jet final states with high multiplicities containing several W's and/or Z's with resulting particle energies similar to W and Z decay, and so with relatively low energy. The requirements on detecting missing energy also dictate a hermetic design, so coverage is required as close to the beam-axis as possible.

Given the precision tracker and a modest energy "dynamic range", much attention has been focussed on applying the principles of energy-flow (EF) to the measurement of jet energies and angles. The concept is : use the tracker to measure charged track energies, use the electro-magnetic calorimeter (ECAL) to separate non-photons from photons and measure photons, and use the hadron calorimeter (HCAL) to separate non neutral hadrons from neutral hadrons and measure neutral hadrons. Since most of the non-charged energy is in photons and the charged particles and many of the neutral hadrons interact in the ECAL, the ECAL performance is crucial to successfully applying the EF concept.

A particularly promising approach applies the principles used in the limited solid-angle Silicon-Tungsten (Si-W) ECALs used for luminosity measurements at SLC and LEP to a 4π detector for the LC [1]. These are sampling calorimeters with layers of Tungsten absorber interspersed with layers of Silicon pads. Despite their technical merits, these approaches appear rather expensive for a large radius ECAL; they also down-weight energy resolution and downplay timing resolution in favor of excellent position resolution and shower imaging power. Better stochastic energy resolution (i.e. higher sampling frequency) would improve the measurement of the predominantly low-energy photons. Excellent timing resolution for bunch identification (ID) is essential for X-band where the bunch crossing time is 1.4 ns, and highly desirable for background rejection (halo-muons, cosmic-rays, back-scatters) and identification of long-lived particles. Note that one expects about one overlaid $\gamma\gamma \rightarrow$ hadrons event with about 100 GeV of calorimetric energy per 100 ns for NLC [2], so bunch ID would be very helpful.

The requirements for calorimetry in the forward region are less well developed and quite different and deserve particular study. Suffice it to say that electron and photon detection are priorities in this harsh environment, and pile-up minimization will be critical.

Plans: We would like to investigate by means of EM shower simulations and physics studies various concepts for the ECAL design and the optimization of these designs, paying attention to all four aspects of the intrinsic ECAL performance : energy, time and position resolution and shower imaging power and also global detector performance characteristics, namely hermeticity, feasibility and cost. Existing concepts such as Si-W with many longitudinal readout layers (eg. 40 as in [3]) and Lead-Scintillator sandwiches such as the Shaslik approach or crystal calorimeters (no longitudinal subdivision) are good examples of very different performance characteristics and cost. Objective evaluation of various approaches to the ECAL requires further understanding of the physics benefits and physics requirements taking into account relevant constraints [1]

The approach which we plan to investigate in detail, particularly regarding feasibility, is a hybrid approach for a compact sampling ECAL. The approach would use Silicon-pad readout planes for excellent position resolution and shower imaging power with a reduced number of longitudinal layers instrumented (eg. 10 instead of 40) and augment this with many fine sampling layers with scintillator. Using scintillator rather than Silicon to do the primary sampling should allow many more layers to be sampled at a lower cost, thus leading to better stochastic energy resolution. The likely choice of absorber is Tungsten - but high cost and difficulties in obtaining thin Tungsten layers imply that Lead should also be evaluated. The design should be compact in order to minimize the Molière radius and thus keep good angular resolution. A high sampling frequency is necessary to ensure good energy resolution and the use of fast scintillators enables excellent timing resolution which can be on the 100 ps level near the shower maximum. Regardless of the eventual utility of the hybrid Si/Scintillator scheme we propose investigating, it is likely that a shower maximum detector designed for good time resolution would benefit any design based on slow readout, and the studies we plan to pursue will be useful for such a detector. Marrying Silicon with scintillator would also give a powerful tool for controlling and localising any non-uniformities in the scintillator response. The design has to make sure that the scintillator sections are integrated properly with the silicon sections in a sensible overall ECAL design.

Sketch of possible approaches to such a hybrid ECAL: Many ways to integrate scintillator readout exist. A conventional approach could use absorber layers and thin scintillating tiles coupled to wavelength shifting (WLS) fibers and clear fibers such as employed for MIP-detection in [4]. Light-yields for very thin tiles are an issue if it is required that each scintillator layer is capable of detecting MIPs, and the insertion of fibres in thin tiles makes homogeneity of response more problematic. However, for the purposes of calorimetric energy resolution and timing resolution, it is not necessary for every single layer to be instrumented individually (layers can be optically summed), and the presence of many Silicon layers assures MIP detection in many layers. One possible method (Figure 1) of extracting the light with minimum dead space would be 5 cm $\times$ 5 cm $\times$ 1 mm scintillating tiles with primary square cross-section (1 mm $\times$ 1 mm) WLS fibers coupled to some or all of the 4 tile edges. Up to four additional secondary (1 mm $\times$ 1 mm) WLS fibers shifting the WLS light to even longer wavelength could integrate the light from many longitudinal samplings running longitudinally at the tile corners. The basic principles have already been applied in eg. [5]. The above dimensions result in only 0.2% of the transverse area being used for longitudinal light propagation if one integrates over the whole shower. Only a few small holes would be needed in the Silicon pad readout planes. Another potential

---

[1] eg. Note that ZHH has been used to justify the Si-W ECAL design, yet without taking into account beam constraints or mass constraints.

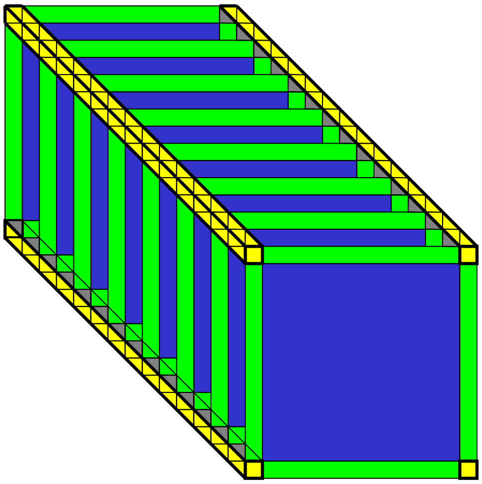

Figure 1: *Illustration of the scintillator part of a possible design: scintillating tiles (blue), primary WLS fibers (green), secondary WLS fibers (yellow).*

approach which may allow a very fine sampling of the shower is to use absorber layers embedded with scintillator with the scintillator read out transversely. This has the advantage of much reduced sampling fluctuations for a fixed sampling fraction with obvious benefits in compactness. Several mechanical solutions come to mind : solid absorber with holes for scintillating fibers (like SPACAL), grooved sheets of absorber to construct an absorber/scintillator matrix, stacked hollow absorber rods etc. This would be followed by transverse readout with WLS bars coupled to secondary WLS fibers as before. Exactly which route to consider with priority depends also on photon detector considerations. Possible choices such as multi-anode photo-multipliers, APDs and Silicon-PMs have very different features in terms of area, noise, quantum efficiency and B-field tolerance.

ECAL Design Study:

We have started looking at the predicted performance of various configurations. As an example we show in Figure 2 the predicted energy resolution for 1 GeV photons for a Tungsten-Scintillator ECAL with 75 sampling layers. The Tungsten thickness is 1.4mm. The dependence on both the scintillator thickness and light-yield is shown.

We have also started looking at the consequences of a hybrid design on the energy resolution. We are encouraged to find that there is a slight anti-correlation (typically -20%) between the energy measurements in scintillator and silicon leading to small improvements in resolution.

Personnel

Gallagher is a graduate student who has been working on evaluating jet reconstruction performance dependence on detector resolutions in a linear collider detector environment.

Benavidez is an undergraduate student who has been working on GEANT4 simulations of sampling calorimeter energy resolution and the optical simulation of a tile-fiber setup.

Hensel is a post-doctoral researcher who joined us in February 2003 and has experience with physics analysis, detector simulations and scintillator-based detectors. Hensel will spend up to 50% of his time on linear collider work once he has established his research work with D0.

Baringer, Bean, Besson and Wilson are faculty. Wilson has been involved in linear collider work since 1995 while working on the OPAL detector at LEP. He has worked on studies of the linear collider

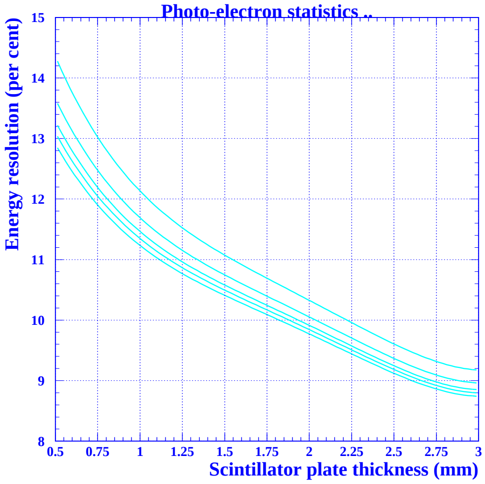

Figure 2: *Energy resolution vs scintillator sampling thickness. The lowest curve shows the contribution from only sampling fluctuations. The four upper curves include the effect of photo-electron statistics with assumptions of 2.5 photo-electrons/mip/mm (upper curve), 5.0 pe/mip/mm, 10.0 pe/mip/mm and 20.0 pe/mip/mm. Note the suppressed zero.*

detector concept: notably hermeticity and forward tracking requirements. He has also contributed to several physics studies: measuring the average centre-of-mass energy, measuring extra-dimensions and measuring the W mass at threshold. He brings to the project a strong appreciation of the physics needs and a background of experience in calorimetric detectors. He has been supervising the work of Gallagher and Benavidez. Baringer, Bean and Besson all have experience from e^+e^- colliders including SLC, PEP and CESR. Baringer has experience with scintillator-based detector elements. Bean and Besson are also involved in the RICE experiment at the South Pole doing calorimetry with radio-waves, and Besson has experience with shower simulations.

FY2004 Project Activities and Deliverables

Investigate the transverse and longitudinal segmentation dependence of the performance of the Si-W ECAL concept and the hybrid Silicon and Scintillator readout concept for a range of potentially achievable detector characteristics. Performance issues that will be investigated are single particle energy, angular and directional resolution vs energy, photon-pion separation vs energy and time resolution. We have started these studies with a full MC shower simulation package with a detailed geometry. For the electro-magnetic showers, GEANT4 is being used. We plan to cross-check the results with EGS or GEANT3. Checking results with a different code will increase confidence in the results[2].

Evaluate the utility of timing resolution with respect to pile-up (does adding 4 or 5 bunch crossings matter to the physics).

Complete and document the study of the physics impact of various detector resolution assumptions.

Build a collaboration with existing and new interested parties in the U.S. and internationally.

Develop further the concept of the hybrid Silicon and Scintillator readout, if the performance prospects studies are encouraging. Identify promising directions and plan specific lab. work aimed at demon-

---

[2] although it is no substitute for test-beam

strating the key features of the particular design: eg. mechanical construction, light yield, uniformity, attenuation length.

FY2005 Project Activities and Deliverables

Continue performance studies of various designs including emphasis on the overall physics performance.

Begin lab. work aimed at validating the design in preparation for proto-type development.

Mechanical studies related to constructing such a calorimeter: tolerances, robustness.

Tests of light yield, uniformity and attenuation length using a β-source and a cosmic-ray test-stand.

Tests of photo-detectors matched to project requirements.

Based on test results iterate prototype design and propose building such a prototype to the consortium. Together with favorable review and more collaborators plan prototype construction and testing.

FY2006 Project Activities and Deliverables

Build prototype ECAL module/modules to demonstrate the required performance of the Scintillator + Absorber part of the design in terms of energy resolution and time resolution. It would be preferable to integrate Silicon readout at this stage - in order to test the overall energy and angular performance. This would require early convergence on such a concept from advocates of both approaches.

Beam tests with electrons, muons and pions.

Budget justification

FY2003. Computers, domestic and international travel, graduate student, 1 undergrad.

FY2004. 0.2 FTE Technician, graduate student, 2 undergrads, domestic and international travel, 0.25 FTE post-doc, equipment (source, cosmic-ray test stand, scintillators, optical readout, photo-detectors, absorber), machine shop labor.

FY2005. 0.3 FTE Technician, graduate student, 0.5 FTE post-doc, equipment (KU share in prototype module), machine shop labor, 2 undergrads, domestic and international travel.

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

Item	FY2004	FY2005	FY2006	Total
Postdoctoral Associates	0	10.893	22.878	33.771
Other Professionals	0	7.351	11.578	18.929
Graduate Students	16.000	16.800	17.640	50.440
Undergraduate Students	4.400	9.240	9.702	23.342
Total Salaries and Wages	20.400	44.284	61.798	126.482
Fringe Benefits	0.816	6.150	10.742	17.708
Total Salaries, Wages and Fringe Benefits	21.216	50.434	72.540	144.190
Equipment	0	35.000	45.000	80.000
Travel	5.000	6.000	12.000	23.000
Materials and Supplies	6.000	10.000	14.000	30.000
Other direct costs	0	0	0	0
Total direct costs	32.216	101.434	143.540	277.190
Indirect costs	14.175	29.231	43.358	86.764
Total direct and indirect costs	46.391	130.665	186.898	363.954

References

[1] J. Brau, A. Arodzero, and D. Strom, Snowmass 1996 proceedings, pp 437-441.

[2] LC Physics Resource Book for Snowmass, May 2001.

[3] TESLA Technical Design Report, March 2001.

[4] G. Aguillion et al., NIM A417 (1998) 266.

[5] J. Fent et al., NIM 211 (1983) 315.

5.4 Fast Response Tile Scintillation Development for Calorimetry and Tracking in NLC Detectors

Personnel and Institution(s) requesting funding

B. Baumbaugh, M. Hildreth, D. Karmgard, A. Kharchilava, J. Marchant,
M. McKenna, R. Ruchti, M. Wayne, J. Warchol, M. Vigneault
University of Notre Dame, Notre Dame, Indiana 46556

Project Leader

M. Hildreth
mikeh@undhep.hep.nd.edu
(574) 631-6458

Project Overview

Scintillation detection has a long history in particle physics. Scintillators are used for example in particle tracking and calorimetry (e.g.; the DØ fiber tracker and the Compact Muon Solenoid (CMS) calorimeters), and many other particle measurement systems. High luminosity accelerators such as the Next Linear Collider (NLC) present a new set of challenges for the development of scintillation detectors which can function effectively in short time, high radiation environments. The challenge is to develop new types of Wave Length Shifting (WLS) fibers which are fast, radiation hard, and efficient. Such a development would have immediate application to both Calorimetry and particle track triggering. The effort to develop such materials requires efforts in the chemistry of scintillating plastics and the geometry of the WLS. This proposal concentrates on the study of the geometric properties of WLS fibers.

These proposed studies have a possible application in many parts of an LC detector. They could be applied to fast triggering and particle tracking as well as calorimetry and calorimeter based clustering. They also have many possible applications outside of high energy physics (e.g.; fiber optic communications). A complimentary study which is necessarily a part of our proposal is that of the photo-sensor system. We shall, in undertaking this study, also have to consider the various possible methods of photo-detection (HPDs, APDs, Photomultiplier's, VLPC, etc.) to find the best possible match for an improved system of WLS fibers.

This proposal seeks to incorporate fast wave-shifting fibers to read out small scintillating tiles for fast timing in calorimetry and preshower/track-triggering applications in LC detectors.

Our objectives are several-fold:

1. Compare and study the performance of conventional Y11/K27 wave-shifter fiber embedded in small standard scintillation tile materials such as Bicron 408 with new, much faster and brighter wave-shifters. If successful, these new materials would provide superior timing information to conventional materials for calorimetry and triggering applications;
2. Develop improvements in fiber-optic light timing by special shaping of the ends of fiber waveguides;
3. Reduce the number of readout channels for fiber-based detectors through the chaining of spaced, non-adjacent scintillating tiles on a single wave-shifting fiber.

The first task involves comparative studies of BC408 scintillator tiles read out with Y11 wave-shifter fiber and BC408 tiles read out with fiber containing recently developed wave-shifter dyes such as

DSB1 and DSF1. The new wave shifters are a factor of 3 faster than Y11 (2.5 ns vs. 8 ns), with a brightness improvement of up to 50%. These would afford significantly improved timing information for preshower and triggering detectors. Tests will be carried out using radioactive sources to study efficiency and uniformity of response. Photo-sensors will be conventional, red-extended multialkali photomultiplier tubes.

The second task involves optical interface modification at the ends of wave-shifter fibers. In most detector applications, the bulk of the light signal within a scintillating or wave-shifter fiber propagates near the critical angle. In a multiclad fiber with core of index 1.59 and outer clad of index 1.42, this angle is approximately 27 degrees relative to the fiber axis. By tapering the end of the fiber (like sharpening a pencil) to approximately this angle, light trapped at the critical angle will emerge from the surface parallel to the fiber axis. This axial light can then be injected into any fiber waveguide (for example PMMA core or even quartz fiber) and can be transmitted with less optical absorption and over a potentially shorter optical path than would otherwise be possible. Such a technique is also applicable to improved timing performance for a calorimeter or trigger detector. For these studies, light excitation would be via blue LEDs and light detection via pin diodes.

The third task is a scheme to reduce the number of readout channels in a multi-channel scintillation tile detector through the multiplexing of non-adjacent scintillating tiles of small size through a common wave-shifter fiber. For example, a series of 100 small, optically isolated, scintillation tiles of 2.5 cm length and 2.5 cm width are arranged end-to-end in a column and lying in a plane. Rather than having 100 individual fiber readouts for these tiles, every 20th tile is read out by a common wave-shifter fiber. (Tiles 1, 21, 41, 61, 81 have a common readout; tiles 2, 22, 42, 62, 82 have a common readout, etc.) In this configuration, the tiles are spaced 50 cm apart along a fiber, corresponding to a light signal timing difference of approximately 3 ns between successive tiles. If the signal arrival time at a photosensor is measured, then the tile producing the signal (and its location) is identified. In this example, a factor 5 reduction in the number of electronics channels results. Our objective is to determine the minimum effective tile separation possible for a given combination of scintillator and wave-shifter. Here, the identification of new, fast wave-shifter materials (first task above) is a major aid to such readout scheme. The optical signals can be detected with photomultipliers or visible light photon counters (VLPC).

FY2003 Project Activities and Deliverables Project activities for the first year are the preliminary testing of the described systems. We intend to conduct an extended feasibility study to determine if the ideas presented have merit. In addition to the construction of a test stand and basic measurements, we will use the data gathered to generate software simulations of the systems. We may then use these to more rapidly study the details of various design possibilities. The first year deliverable is a complete feasibility study.

FY2004 Project Activities and Deliverables Presuming that the first years efforts bear fruit, project activities in the second year center around building a working prototype system using the elements described in this proposal. The deliverables are the prototype and documentation of the physics capabilities of the system.

FY2005 Project Activities and Deliverables In the third year the project aims to take the lessons learned from the working prototype system to design a detector subsystem compatible with the needs of an NLC detector. The deliverables are a Technical Design Report of such a system.

Budget justification

We request half-time support and later full-time support for a technician to coordinate the design and fabrication of the test assemblies of the scintillation tile and wave-shifter arrays. This individual will, with the assistance of a graduate student, supervise the work of a high school teacher and several high school students during the summer to construct tile/fiber networks and to develop a test station to evaluate the performance of these structures. The graduate student will be supported from base grant funds.

An additional facility will be developed to shape the ends of optical fibers with the aim of developing optical connectors to adjust the phase space of the light propagating in the fibers to reduce propagation time and improve light transmission in optical fibers of long length.

Equipment funds for the purchase of fast photo-sensors and materials funds for scintillating tiles and wave-shifting fibers are requested. A very modest travel budget is included to support several laboratory and vendor visits.

Indirect costs are estimated at 48.5% of modified total direct costs according to University of Notre Dame Accounting Practices.

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

Item	FY2003	FY2004	FY2005	Total
Technician	22.833	23.458	41.167	87.458
Fringe Benefits	4.567	4.692	8.233	17.492
Total Salaries, Wages and Fringe Benefits	27.400	28.150	49.400	104.950
Equipment	2.500	2.500	2.500	7.500
Travel	1.000	1.500	2.000	4.500
Material and Supplies	2.500	2.500	2.500	7.500
Total direct costs	33.400	34.650	56.400	124.450
Indirect costs	14.987	15.593	26.142	56.722
Total	48.387	50.243	82.542	181.172

5.5 Development of particle-flow algorithms, simulation, and other software for the LC detector

Personnel and Institution(s) requesting funding

G. Blazey, D. Chakraborty, J. G. Lima, A. Maciel, J. McCormick, V. Zutshi.
Northern Illinois Center for Accelerator and Detector Development/ Northern Illinois University

Collaborators

S. Magill et al., *Argonne National Laboratory,*
J. Yu et al., *University of Texas at Arlington,*
N. Graf et al., *Stanford Linear Accelerator Center,*
M. Oreglia et al., *University of Chicago,*
R. Frey et al., *University of Oregon,*
U. Nauenberg et al., *University of Colorado, Boulder*,
G. Wilson et al., *University of Kansas,*
U. Mallik et al., *University of Iowa*.

Project Leader

D. Chakraborty
`dhiman@fnal.gov`
(630)840-8569

Project Overview

The Northern Illinois University(NIU)/Northern Illinois Center for Accelerator and Detector Development (NICADD, `http://nicadd.niu.edu`) group is interested in calorimeter R&D for the proposed LC. Our group proposes to develop, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet reconstruction using particle-flow algorithms (PFA, see below), also known as energy-flow algorithms (EFA). Simulations/algorithm development and hardware prototyping are envisaged as the two main components of our efforts. This proposal addresses the first component while the second is the subject of a separate proposal.

An e^+e^- linear collider is a precision instrument that can elucidate Standard Model (SM) physics near the electroweak energy scale as well as discover new physics processes in that regime, should they exist. In order to get the most out of the potential anticipated from a machine of this type, the collection of standard high energy physics detector components comprising an experiment must be optimized, sometimes in ways not yet realized at current experiments. One such example is the hadron calorimeter which will play a key role in measuring jets from decays of vector bosons and other heavy particles such as the top quark, the Higgs boson(s), etc. In particular, it will be important to be able to distinguish, in the final state of an e^+e^- interaction, the presence of a Z or a W boson by its hadronic decay into 2 jets. This means that the dijet mass must be measured within $\sim$ 3 GeV, or, in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ (E in GeV). Such high precision in jet energy measurement cannot be achieved by any existing calorimeter in the absence of a kinematically overconstrained event topology. Similar precision in measurements of jet and missing momentum will be crucial for discovery and characterization of several other new physics processes as well as for precision tests of the Standard Model. Such ambitious objectives place stringent demands on the performance of the caloriemters working in conjunction with the tracking system at the LC, and requires development of new algorithms and technology in this sphere.

The most promising means to achieving such unprecedented jet energy resolutions at the LC is through particle-flow algorithms (PFA). A PFA attempts to identify in a jet its charged, electromagnetic, and neutral hadron components, in order to use the best means to measure each. separate and measure in a jet clusters of energy initiated On average, neutral hadrons carry only $\sim$11% of a jet's total energy, which can only be measured with the relatively poor resolution of the HCal. The tracker is used to measure with much better precision the charged components ($\sim$60% of jet energy), and the electromagnetic calorimeter (ECal) to measure the photons with a resolution $\sigma(E) < 0.15\sqrt{E}$ ($\sim$25% of jet energy). A net jet energy resolution of $\sigma(E) \approx 0.3\sqrt{E}$ is thus achievable by using the HCal only to measure the charged hadrons with a resolution $\sigma(E) \approx 0.6\sqrt{E}$.

A calorimeter designed for PFAs must be finely segmented both transversely and longitudinally for 3-D shower reconstruction, separation of neutral and charged clusters, and association of the latter to corresponding tracks. This requires realistic simulation of parton shower evolution and of the detector's response to the particles passing through it. The latter relies heavily on analysis of beam test data. The detector optimization requires the simulation, visualization, and analysis packages to be highly flexible, which can only be achieved through careful design and implementation of the software itself. Very large numbers of events will have to be simulated to evaluate the impact of competing designs on physics capabilities. Characterization of signatures arising from processes predicted by some extensions of the SM will require simultaneous coverage of broad ranges of undetermined parameters. Parametrized fast simulation programs will thus have to be developed once the algorithms have stablized. Parametrization of PFAs will require much work, and is one of our key objectives.

In January 2002, members of NIU, UTA (the University of Texas at Arlington), and ANL began collaborating on PFAs, simulations, and software development efforts. Many of the results that emerged through discussions at our regularly scheduled meetings have been presented at the CALOR 2002 conference; ECFA/DESY meetings at St. Malo, Prague, and Amsterdam; the American LC workshops in Santa Cruz, Arlington, and Ithaca; and at the International LC Physics and Detector Workshop in Korea.

Toward the optimization of the HCal design, the NIU+ANL team have started investigating both analog (cell energy measurements) and digital (hit counting) readout methods as functions of the cell size. Our preliminary findings indicate that for small enough cell sizes, the digital method yields a more precise measurement of the hadron energy, suggesting that hit density fluctuations are smaller than visible energy fluctuations in a hadronic shower. Three independent approaches to the implementation of an PFA are taking shape. These will help us determine the optimal cell sizes and geometry for best charged/neutral hadron shower separation in jets within the context of some specific overall detector parameters. Our HCal optimization efforts can be summarized as follows:

HCal absorber/active media properties: The detector simulation and analysis of physics events within the Java Analysis Studio (JAS)-based software environment developed at SLAC, is flexible in the choice of absorber and active media type and thickness within the limits of the HCal volume. Our group has recently put together a GEANT4-based detector simulation package to work within this environment, and produced many data sets spanning a range of cell shapes and sizes, and particle types. Teams from ANL and SLAC, in addition to NIU, are studying a wide variety of events simulated with this package. We will optimize the HCal by comparing dense materials (W, Pb) to less dense ones (Cu, Stainless Steel, Brass) as absorbers using as performance measures the containment of hadronic showers, the density of hits, and single particle energy resolution.

HCal transverse granularity/Longitudinal segmentation: We plan to optimize the 3-D granularity of cells for the most promising PFAs and then determine an optimal active medium for the desired cell size. The methods developed here are generalizable to different total detector geometries, i.e., SD, LD, TESLA, etc. The basic performance measure here is the ability to separate showers from charged and neutral hadrons - the key to any PFA.

Analog vs. digital readout: Once the optimal 3-D granularity has been determined, the choice of the readout method can be evaluated by comparing jet resolutions with both analog and digital readout. It may be prudent to consider both the best analog and the best digital version of the HCal for eventual evaluation with test beams provided both prove potentially capable of meeting the energy resolution requirement. Testing both options will allow for future advances in readout technology which might favor one option over another.

Particle-flow algorithms: For the first time in calorimeter development, it is necessary to include the reconstruction program in the optimization of the detector. It is anticipated that the choice of a PFA will ultimately prove a key factor in the achievement of the best jet energy resolution. As a first step, we plan to implement a PFA that does not require calorimeter cell clustering. Rather, it relies on associating calorimeter cells to extrapolated tracks, substituting the track momentum for the calorimeter energy measurement, finding photons in the ECal based on analytical shower shapes, applying an appropriate jet algorithm with the tracks and photons as input, and finally, associating the remaining calorimeter cells within the jet cone to the jet (these are predominantly due to neutral hadrons).

The NIU group has been working on simulation software since early 2002 and has made significant progress. All of the current American LCD simulation software, both event generation and a detector simulation based on the “GISMO” package, has been ported to the Linux platform. Since April, 2002, we have been processing simulation requests from several groups engaged in LC R&D, on a 40-node Linux farm allocated to us by Fermilab. We have recently developed, in close collaboration with the ALCPG simulation group, a GEANT4-based simulation package based on standard C++ that is completely independent of any specific analysis platform. The new package, named “LCDG4”, fully complies with the model put forth by the simulation group, and adds some useful functionalities to it. Upon completion of tests currently underway, this package is expected to become the standard for ALCPG. Subsequently, it should be integrated into the U. of Chicago/ANL GRID facility currently under development. We organized a workshop at NIU/NICADD in November, 2002 (`http://nicadd.niu.edu/ws/`), to bring the groups together, chart a plan, and set out in an organized manner.

Further, as members of the CALICE collaboration (CAlorimeter for the LInear Collider with Electrons, `http://polywww.in2p3.fr/flc/calice.html`), and in active cooperation with our counterparts in the TESLA collaboration, we are working very closely with our European colleagues. In particular, the TESLA group has its own Geant4-based simulation package, called “Mokka”, which has a somewhat more powerful geometry description system, but lacks the flexibility and the sophisticated input-output options of LCDG4. We are working together to combine the best features of both, plus a more advanced geometry description system, into a universal package that can be used to compare different detector designs and algorithms in a uniform manner. Indeed, a first combined version called “LCDMokka” has just materialized, and is being tuned. For a more sophisticated mechanism for run-time geometry description, we are considering the possibility of reviving GDML (Geometry Description Markup Language), a Geant4-specific extension of XML. The development of GDML was initiated by CERN, but frozen at a late stage when it became clear that it would not be ready soon enough to be useful for CMS and ATLAS. The initial prognosis on GDML looks promising from our point of view.

Among the members of our group we have adequate experience in calorimeter hardware, electronics, reconstruction software, and algorithm development. We anticipate close collaboration with other groups who have similar interests. Active links have been established with ANL, SLAC, U. of Chicago, DESY, members of the CALICE collaboration, and several other institutions.

Activities outlined in this proposal are also synergistic to the proposals for hardware prototyping of different technology choices. We will maintain close communication with the groups involved in hardware development for the ECal and the HCal.

FY2004 activities and deliverables

During the first year we will concentrate on two things: first, the preparation of a comprehensive design document for the simulation software suite (in collaboration with several groups across the world), and second, development of PFAs for the electromagnetic and hadronic calorimeters. Both analog and digital versions of the algorithms will be investigated for the hadronic section. The first year deliverable will be a first version of a class of particle-flow algorithms based on full simulation and reconstruction of the calorimeter and the tracking system. Completion of the simulation design document is also foreseen, although it depends to a large extent on other groups as well. In addition, the standard GEANT4-based simulation facility (farm+server) will be available for to the entire LC community through a web-based request form.

FY2005 activities and deliverables

Apart from further tuning of the algorithms, extensive studies of critical physics processes will be carried out to understand the impact of the calorimeter performance on the physics program of the Linear Collider. These studies will employ analog and digital versions of our PFAs. The second year deliverables will be a quantified assessment of physics reach vs calorimeter performance for the Linear Collider with a clear statement on the desirability of a digital or analog option for the hadronic calorimeter.

FY2006 activities and deliverables

In the third year we will embark on the development of parameterized simulations of the particle-flow algorithms. The technology and geometry are expected to have been narrowed down by that time setting the stage for such parametrized fast simulation for extensive physics studies. The third year deliverable will be a fast simulation program based on PFAs. Also in the plans for the third year is a detailed simulation program for the different prototype modules that are expected to be studied at a test beam facility in 2006.

Three-year budget, in then-year K$

Item	FY2004	FY2005	FY2006	Total
Post-doctoral Associates	0	43.500	44.805	88.305
Graduate Students	39.000	30.128	31.031	100.159
Undergraduate Students	0	0	0	0
Total Salaries and Wages	39.000	73.628	75.836	188.464
Fringe Benefits	0	19.140	19.714	38.854
Total Salaries, Wages and Fringe Benefits	39.000	92.768	95.550	227.318
Equipment	0	25.000	23.000	48.000
Travel	10.000	20.600	21.218	51.818
Other direct costs	0	0	0	0
Total direct costs	49.000	138.368	139.768	327.136
Indirect costs (26% of non-equipment)	12.740	29.476	30.360	72.576
Total direct and indirect costs	61.740	167.844	170.128	399.712

Budget justification

The first year's activities revolve around the development of particle-flow algorithms. This will involve NICADD staff members (not included in the budget shown here), and 2.0 FTE graduate students. Optimization and detailed performance studies of the algorithm will be carried out in the second year by 1.5 FTE graduate students and 1.0 FTE post-doc with additional support from NICADD staff. During the third year, the development of parameterized simulations will be supported by 1.0 FTE post-doc, together with 1.5 FTE graduate students. Communication of progress and exchange of ideas through international workshops and conferences will be crucial for our endeavor to have a global impact. We estimate four domestic trips at $1.5K each and two international trips at $2.0K each during the first year, and twice as many in the second and third years. The equipment cost accounts for a 10-CPU Linux mini-farm + file server which will be needed in early FY05 to augment the allocation from Fermilab, as the simulation service enters a serious production phase. This additional capacity will have to be doubled toward the end of FY 2006.

Fringe benefits to personnel at NIU's mandated rate of 44% of salary, and indirect costs at a specially negotiated rate of 26% (instead of the usual 45%) are included in the requested amount.

Existing Infrastructure and available resources

The above requested resources will be augmented by the following support, totaling approximately $500K, from other sources:

(a) NIU/NICADD personnel,

(b) ANL personnel,

(c) Computing hardware and support provided by NICADD,

(d) 40-CPU Fermilab Linux farm (run by NIU personnel). These machines are relatively old, with per-CPU-capacity roughly a quarter of those requested in this proposal.

6 Muon System

6.1 Scintillator Based Muon System R&D

Personnel and Institution(s) requesting funding

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

Collaborators

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

Project Leader

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

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

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

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

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

FY2004 Project Activities and Deliverables

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

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

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

FY2005 Project Activities and Deliverables

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

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

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

FY2006 Project Activities and Deliverables

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

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

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

Budget justification

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

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

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

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

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

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

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

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

(1) Engineering work

(2) 20% of “Other Professionals”.

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