Calorimetry Table of Contents

Table of Contents and Overview .................................................................6.0

Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter ...........6.1

Linear Collider Detector Development Proposal to Study and Develop Scintillator-Fiber Readout Scintillator Calorimetry with High Spatial Resolution ..............................6.2

Fast Response Tile Scintillation Development for Calorimetry and Tracking in NLC Detectors .................................................................................................................6.3

Exploring Crystal Calorimetry for A Linear Collider Detector .............................6.4

Development of a silicon-tungsten test module for an electromagnetic calorimeter ......6.5

Digital Hadron Calorimetry for the Linear Collider using GEM technology .............6.6

(this proposal has been merged with another) .................................................6.7

(this proposal has been merged with another) .................................................6.8

Development of energy-flow algorithms, simulation, and other software for the LC detector .....................................................................................................................6.9

Investigation and Design Optimization of a Compact Sampling Electro-magnetic Calorimeter with High Spatial, Timing and Energy Resolution .............................................6.10

Optimization of LC detector elements for physics analysis ..................................6.11

Micro-machined Vacuum Photodetectors .........................................................6.12

Cherenkov compensated calorimetry ..................................................................6.13

Study of Resistive Plate Chambers as Active Medium for the HCAL .....................6.14
**Introduction to Calorimeter R&D**

To explore the uncharted territory of the Electroweak symmetry breaking energies, identification of $Z$, $W$ and Higgs from their respective reconstructed decays is critical. This requires good lepton identification and very good jet energy resolution so that reconstructed jet-jet energies can be accurately measured.

The most important aspect of the calorimeter is to provide accurate measurements of the four-momenta of the charged and the neutral particles, individually and in jets. In the present parlance of calorimetry, this is best achieved by the Energy Flow algorithm in three dimension. The Energy Flow Algorithm consists of following the tracks measured by the tracking detector into the calorimeter and measuring the respective energy deposits; [neutrals are measured by the calorimeter only]. This scheme needs separation of the electromagnetic ($e$, $\pi^0$, $\gamma$) and the hadronic components in ECAL and HCAL by their respective energy deposits, good association of tracks from jets with the appropriate calorimeter clusters, and charged and neutral hadron cluster separation. (For example, $K_L$'s are to be identified by their energy deposits in the electromagnetic and the hadronic calorimeter).

The Energy Flow scheme clearly requires a highly segmented calorimeter, both laterally and longitudinally. In principle, once the energy flow is fully accomplished, the long-coveted similar response to electrons and hadrons, namely, $e/h \sim 1$, should not be necessary, since energy deposited by each particle will be measured individually. However, to what extent this can be accomplished needs to be tested both by realistic simulations, and in beam tests.

A number of sub-proposals, C, D, and E, shown in the table below, are about various simulation studies, in particular, regarding Energy-Flow and various types of optimizations. Sub-proposal E is presently attempting the simulation of some of the proposed technology choices prior to developing an EM calorimeter. The second part of C includes developing readout electronics and is also part of sub-proposal L.

<table>
<thead>
<tr>
<th>Sub-proposal</th>
<th>UCLC</th>
<th>Description</th>
<th>Principal Investigator</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. UCLC</td>
<td></td>
<td>Optimization of LC Detector Elements for Physics Analysis</td>
<td>Mark Oreglia</td>
<td>University of Chicago</td>
</tr>
<tr>
<td>D. UCLC</td>
<td></td>
<td>Development of Energy-Flow Algorithms, Simulation and Other Software for the LC Detector</td>
<td>Dhiman Chakroborty</td>
<td>NICADD</td>
</tr>
<tr>
<td>E. UCLC</td>
<td></td>
<td>Investigation and Design Optimization of a Compact Sampling EM Calorimeter with High Spatial, Timing and Energy Resolution</td>
<td>Graham Wilson</td>
<td>University of Kansas</td>
</tr>
</tbody>
</table>

Sub-proposals F and G, shown in the table below, are to study a finely segmented Silicon-Tungsten electromagnetic calorimeter and a longitudinally (in addition to laterally) segmented electromagnetic crystal calorimeter. Both proposals include simulation studies as well.
Shown below are a number of proposed calorimeters with scintillators of various types, H, I and J. Sub-proposal I specifically mentions HCAL. Two different types of hadron calorimeters are also proposed, sub-proposal K proposes use of GEM-based technology and sub-proposal L proposes use of glass RPC's. As part of the study, simulation is included in H, I and K.

The sub-proposal M is based on the use of Cerenkov compensated Calorimetry to provide event-by-event compensation by exploiting ionization and the Cerenkov radiation.
6.1. Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter (UCLC)

Calorimetry

Contact person: Vishnu Zutshi
email: zutshi@fnal.gov
phone: (630) 840-5764

NIU
Illinois-Chicago

FY 2003: $71,510
FY 2004: $158,490
FY 2005: $287,040
Proposal Name
Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter.

Classification (accelerator/detector: subsystem)
Calorimeter: Hadron Calorimeter.

Personnel and Institution(s) requesting funding
M. Arov, G. Blazey, D. Chakraborty, A. Dyshlant, M. Martin, R. McIntosh, V. Rylalin, 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. Oregeia 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.*

Contact Person
V. Zutshi
zutshi@fnal.gov
(630)840-5764

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/algorithms 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 $\sqrt{s} = 13\,\text{TeV}$ collider is through energy flow algorithms (EFA) which require fine lateral and longitudinal segmentation of the calorimeter (see below). We propose to conduct a comprehensive feasibility study of a finely segmented hadron calorimeter with transverse cell cross section of $\approx 16\,\text{cm}^2$ 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 readout is a potential solution. At the 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 D0 experiment and elsewhere. The NIU/NICADD team has already started investigating a sampling digital hadron calorimeter with scintillator as the active medium. This capitalizes on proven detection techniques and well known readout devices. Absence of fluids, high-voltage, and 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.

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 routings have been machined and are being evaluated together with fibers of different shapes, dimensions and optical treatments. Sufficient strength and excellent uniformity of response has been obtained using extrudable groove shapes. Apart from the relative light yield measurements for these various configurations, absolute measurements are also being carried out with the help of Visible Light Photon Counters (VLPC) as photo-detectors which have a quantum efficiency of $\approx 70\%$ but require an operational temperature of liquid helium. Metal resistive structures, an emerging technology which offers quantum efficiencies $\approx 30\%$ at room temperature, are also being considered. In addition, various choices for absorber material, investigation of tooling and mechanical assembly options and the use of extruded scintillator are slated for study.

**FY2003 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 (VLPC’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.

**FY2004 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. Construction of a 7-cell wide and 12-layer deep test module will begin. The second year deliverable will be a full Linear Collider detector simulation incorporating our HCAL design based on a user-friendly geometry definition language, a decision on the type of photodetector we want to use for the scintillator-based HCAL and the construction of a module for cosmic-ray tests.
FY2005 activities and deliverables
During the third year we will complete the construction of prototype module(s) for cosmic ray and beam tests, collect and analyze data with them. A full specification of the support structure and fiber routing scheme of the HCAL module design 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.

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. for extruder operation,
(d) NIU machine shops,
(e) Collaboration with Fermilab chemists on extruder dyes,
(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
FY2003: 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.

FY2004: Operation of the extrusion line and construction of the test module for will be done with the additional support of an engineering physicist (0.5 FTE, NIU) and a post-doc (0.25 FTE, UIC). Some additional equipment will be required to prepare for cosmic ray tests. The need for new materials and supplies is expected to remain roughly the same as in FY2003.

FY2005: Cosmic ray and beam tests and a full specification of the mechanical design of the HCAL and tooling for automated tower assembly will require an engineering physicist (0.5 FTE, NIU) a post-doc (0.5 FTE, UIC) in FY2005. Support will be needed for an additional 0.5 FTE graduate student (NIU). Much larger amounts of materials and supplies will be needed to build the final test modules. Photodetectors, readout electronics, and a data acquisition system for the tests account for the equipment request.

The travel funds will cover costs of travel by group members to between collaborating institutions for the purpose of this project only.

Three-year budget: see next page
### Three-year budget, in then-year K$ (NIU)

<table>
<thead>
<tr>
<th>Item</th>
<th>FY 2003</th>
<th>FY 2004</th>
<th>FY 2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>0</td>
<td>41.0</td>
<td>42.5</td>
<td>83.5</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>18.5</td>
<td>19.5</td>
<td>30.5</td>
<td>68.5</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Salaries and Wages</strong></td>
<td>18.5</td>
<td>60.5</td>
<td>73.0</td>
<td>152.0</td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>0</td>
<td>8.5</td>
<td>9.0</td>
<td>17.5</td>
</tr>
<tr>
<td><strong>Total Salaries, Wages and Fringe Benefits</strong></td>
<td>18.5</td>
<td>69.0</td>
<td>82.0</td>
<td>169.5</td>
</tr>
<tr>
<td>Equipment</td>
<td>15.0</td>
<td>8.0</td>
<td>50.0</td>
<td>73.0</td>
</tr>
<tr>
<td>Travel</td>
<td>1.5</td>
<td>3.0</td>
<td>6.0</td>
<td>10.5</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>5.0</td>
<td>5.0</td>
<td>35.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total direct costs</strong></td>
<td>40.0</td>
<td>85.0</td>
<td>173.0</td>
<td>298.0</td>
</tr>
<tr>
<td>Indirect costs (44% of non-equipment)</td>
<td>11.0</td>
<td>33.9</td>
<td>54.1</td>
<td>99.0</td>
</tr>
<tr>
<td><strong>Total direct and indirect costs</strong></td>
<td>51.0</td>
<td>118.9</td>
<td>227.1</td>
<td>397.0</td>
</tr>
</tbody>
</table>

### Three-year budget, in then-year K$ (UIC)

<table>
<thead>
<tr>
<th>Item</th>
<th>FY 2003</th>
<th>FY 2004</th>
<th>FY 2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>0</td>
<td>11.00 (3 months)</td>
<td>22.00 (6 months)</td>
<td>33.00</td>
</tr>
<tr>
<td>Graduate Students (6 months)</td>
<td>8.85</td>
<td>8.85</td>
<td>8.85</td>
<td>26.55</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Salaries and Wages</strong></td>
<td>8.85</td>
<td>19.85</td>
<td>30.85</td>
<td>59.55</td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>0</td>
<td>3.15</td>
<td>6.30</td>
<td>9.45</td>
</tr>
<tr>
<td><strong>Total Salaries, Wages and Fringe Benefits</strong></td>
<td>8.85</td>
<td>23.00</td>
<td>37.15</td>
<td>69.00</td>
</tr>
<tr>
<td>Equipment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Travel</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>5.00</td>
<td>6.00</td>
<td>8.00</td>
<td>19.00</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>3.05</td>
<td>3.05</td>
<td>3.05</td>
<td>9.16</td>
</tr>
<tr>
<td><strong>Total direct costs</strong></td>
<td>16.90</td>
<td>32.05</td>
<td>48.20</td>
<td>97.16</td>
</tr>
<tr>
<td>Indirect costs</td>
<td>3.60</td>
<td>7.54</td>
<td>11.74</td>
<td>22.88</td>
</tr>
<tr>
<td><strong>Total direct and indirect costs</strong></td>
<td>20.51</td>
<td>39.59</td>
<td>59.94</td>
<td>120.04</td>
</tr>
</tbody>
</table>
6.2. Linear Collider Detector Development Proposal to Study and Develop Scintillator-Fiber Readout Scintillator Calorimetry with High Spatial Resolution (LCRD)

Calorimetry

Contact person: Uriel Nauenberg
e-mail: uriel@pizero.colorado.edu
phone: (303) 492-7715

Colorado

FY 2003: $54,484
Linear Collider Detector Development Proposal
to Study and Develop Scintillator-Fiber Readout Scintillator Calorimetry with High Spatial Resolution

Toshinori Abe, Anthony Barker, Uriel Nauenberg, Joseph Proulx, Shenjian Chen

Department of Physics, University of Colorado
Boulder, CO 80309-0390

July, 2002
Contents

1 The Calorimeter Studies Proposal .................................................. 2
  1.1 Introduction ........................................................................... 2
  1.2 Possible Collaborators .......................................................... 3
  1.3 Supersymmetry Signals .......................................................... 3
  1.4 Proposed Detector Development Study ................................. 4
  1.5 Budget .................................................................................. 9
Chapter 1

The Calorimeter Studies Proposal

1.1 Introduction

We propose to study scintillator based calorimetry with fiber readout using a geometrical configuration where alternate layers are offset relative to one another so that they overlap only a quarter of the previous scintillator plate unit. This is shown in one of the figures below discussing the project. We would like to study the intensity and uniformity of light collection where the fiber is placed straight into the scintillator along the diagonal of a square scintillator piece. In this study we also propose to measure the properties of Avalanche Photo-diodes; in particular their stability, linearity, signal-to-noise ratio, and timing resolution; we propose to use these to provide a signal readout proportional to the light produced in the scintillator. Avalanche Photo-diodes work well in the presence of a magnetic field. A scintillator based calorimeter provides excellent electromagnetic and hadronic shower energy resolution and excellent timing. Both properties are very desirable in the search for new phenomena at the higher energies associated with the Linear Collider.

In the study of supersymmetry we need as good a hadronic jet resolution as possible as well as excellent single particle tracking resolution in order to measure the masses of these states using the energy end-point method. In measuring the masses of the charginos, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$, and the neutralinos, $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$, we need to accurately determine the energies of either
multi-hadronic final states or Ws and Zs which decay into hadronic final states. An accurate measurement of their energies requires excellent calorimetric energy resolution which can best be achieved using new techniques described partly under the rubric of “Energy Flow” for hadronic states. To obtain good signal to background in determining the presence of a W or Z we need to also obtain good directional resolution. I propose, simultaneously, to use a technique that would improve the spatial resolution of photons, hence, improve the directional resolution of $\pi^0$s, a major element of hadronic jets. Similarly we can improve the directional resolution of neutral hadrons.

We propose to involve undergraduate students in this program; the students will be supported by University funds under the “Undergraduate Research Opportunities Program” at the University of Colorado. We have involved many such students in the simulation of reactions where Supersymmetric particles are produced in a Linear Collider and we find their contribution to be of very high quality.

1.2 Possible Collaborators

Graham Wilson, from the University of Kansas, is discussing collaborating on several aspects of this proposal. He is interested in developing further the concept of a tungsten absorber based sampling electromagnetic calorimeter with active layers of two types, silicon pads for fine spatial resolution and scintillator plates with fiber readout for improved energy sampling at modest cost and excellent timing resolution. Good timing resolution benefits background rejection from accelerator induced halo muons and cosmic rays, identification of long lived heavy particles and bunch identification.

Critical areas of scintillator based R&D relate to light yield, timing response, plate size, homogeneity, maximizing sampling frequency and retaining a compact design. Further pursuit of understanding the physics requirements on the detector performance will also aid in evaluating the various design choices.

1.3 Supersymmetry Signals

Our group at Colorado has been studying how to measure the masses and other characteristics of Supersymmetric particles. This work has been carried
out by undergraduates being supported mainly by University funds. This work is recorded in http://hep-www.colorado.edu/SUSY. The analysis is being carried out under the MSSM SUGRA model using the ISAJET [1] software simulation package. We have arrived at the conclusion that, to collect a sufficient number of events in a reasonable period of time, in the determination of the masses of charginos and neutralinos we need to measure the energies of hadronic jets. Hence the need for good calorimetric resolution. The channels we need to observe is the decay into Ws and Zs whose energies we can measure via their decays into hadronic jets. This is needed because a large fraction of their decay branching ratios is into hadronic final states. For example, using the MSSM SPS1 parameters [2] the decay of the $\widetilde{\chi}_1^\pm$ occurs 98.3\% of the time via $\tau_1^\pm$, $\nu$, and only 1.2\% into $W^\pm, \chi_1^0$. It is the second channel that we suggest to use to measure the mass of the $\chi_1^+$ since the first one is heavily compromised by large backgrounds from the $2\gamma$ processes.

During this year we have been studying the signals that are produced in the MSSM SPS1 simulation. There are cases where we need to measure accurately the energy of Ws and Zs. Because the model indicates that the production cross-sections and decay branching ratios are low we need to include the hadronic decays of these Ws and Zs. In the case of Ws only hadronic decay modes can be used to determine the W energy. To get good signal to background we need to have good energy and directional resolution to have good combined mass resolution.

Typical signals that we have studied are shown in Figure 1.1 and Figure 1.2. These sharp edges have been obtained using leptons and hence, the resolution is due to excellent tracking. We would like to get similar resolutions using hadrons; this is the purpose of the study being proposed here.

### 1.4 Proposed Detector Development Study

We propose to carry out a simulation and hardware study of scintillator calorimetry with fiber read out in an arrangement that maintains excellent energy and timing resolution while also improving spatial resolution that leads to improvement in the energy and directional resolution of jets that leads to improvement in the energy and mass resolution of the associated Ws and Zs. We propose to start by studying 5 x 5 cm$^2$ scintillator plates but we can change these depending on cost versus resolution studies. We propose to use a geometrical arrangement as shown in Figure 1.3 and Figure 1.4. This
Figure 1.1: The spectral difference between the electrons and positrons for 80% R electron polarization minus the spectra for 80% L electron polarization. This is the only manner we have found to observe clearly the appropriate edges of the signal to determine the masses of the Left and Right Selectron and the Neutralino.

arrangement will localize the position for showers to an apriori resolution of about 1/4 the size of each plate. In this manner we can also correct for light collection dependence as a function of the shower distance from the scintillating fiber which should help improve the energy resolution of the calorimeter. Since the Moliere radius of the shower is comparable with 1/4 of the plate size (2.5 x 2.5 cm$^2$) we could use light sharing between the various plates to improve on this spatial resolution. The use of scintillator as the detector medium will lead to excellent timing resolution which seems to be essential in the study of signals based on single non-pointing photons.
Figure 1.2: The spectral distribution of electrons or positrons in the case where we observe only an $e^-\mu^+$ or $e^+\mu^-$ after subtracting the $\mu^\pm$ spectrum in the same events since that would represent the background from channels that would occur through $\tau^\pm$ decays. We determined that this channel was the most effective to observe clearly the appropriate edges of the signal to determine masses of the electron sneutrino and the Neutralino.

A preliminary study of the directional resolution improvement is shown in Figure 1.5 where we show the difference in $\phi$ between the reconstructed position and the actual position of a photon striking a plate where there is no offset as compared to when there is. Our preliminary expectation of a factor of 2 improvement is clearly seen. Hence we can expect at least a factor of 4 improvement in the $\delta\phi\delta\theta$ directional resolution of the photon and, hence, of the associated $\pi^0$.

We propose to use a scintillating fiber insertion into the scintillator plate that is a straight line along the diagonal of the scintillating plate. We believe
that placing a fiber in a circle is more demanding and manpower consuming than placing it in a straight line as shown in Figure 1.6. Our experience in building the KTeV anti-counters was that fibers broke often when being inserted into a circular path.

We propose to study the performance of large active areas avalanche photo-diodes (2 cm²) as produced by Advanced Photonics, Inc. and Radiation Monitoring Devices, Inc [3].

The first year tests is to use a radiation source and a triggered cosmic rays using a simple scintillator hodoscope to study the light collection efficiency of a 5 x 5 cm² scintillating plate of various thicknesses covered by tyvek and with various side reflecting materials to observe light collection variations. We also propose to study the efficiency, voltage linearity, light intensity linearity, signal-to-noise ratio, and stability of the avalanche photo-diodes under various temperature environments and various wavelengths.

In later years we propose to actually build a multiplate array to use with an electron beam to study the energy and geometrical resolution of such a calorimeter. The preliminary arrangement for the electromagnetic
Figure 1.4: Geometrical arrangement of 5x5 cm$^2$ scintillator plates where alternate layers are offset. Instead of lead, indicated in the figure, we are considering initially tungsten. This is the z-view of the barrel plates.

calorimeter portion would be 2 mm tungsten plates alternating with 2 mm thick, 5 x 5 cm$^2$ scintillator plates. We believe 1 mm scintillator plates are too thin to be used with $\approx$ 1 mm diameter fibers. Then we would plan to use a similar arrangement for a hadronic calorimeter to be used with the “Energy Flow” concept to determine how much we can improve the hadronic jet energy and direction.

In the same period we propose to carry out software simulation studies to determine the expected improvement in $\pi^0$ and hadron energy and direction resolution and therefore associated jet energy and directional resolution. We would like to study the use of “neural nets” in the determination of jet energies. In particular we would like to investigate the usefulness of a disk file of actual hadronic showers versus incident hadron energy. We would like to compare the observed shower pattern with the patterns on disk using neural nets and determine whether this technique would further improve the directional and energy resolution of jets.
Figure 1.5: Difference in $\phi$ between the actual position of a photon shower and assuming it is at the geometrical center of the tile array for a calorimeter with no offset plates and that where the plates are offset. The photon is striking the barrel calorimeter normal to the surface.

1.5 Budget

The budget request by the University of Colorado is for the partial support of a Research Associate, request for equipment funding to be shared with the University, request for supplies and materials and travel to meetings of the American LCD group.
Figure 1.6: This figure shows the placement of the fiber in the scintillator plate.

Budget Request

<table>
<thead>
<tr>
<th>ITEM</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. SALARIES AND WAGES</strong></td>
<td></td>
</tr>
<tr>
<td>Research Associate:</td>
<td></td>
</tr>
<tr>
<td>To be named; 50% time 12 mos.</td>
<td>20,000</td>
</tr>
<tr>
<td>Research Assistant:</td>
<td></td>
</tr>
<tr>
<td>Joseph Proulx; 100% time 12 mos.</td>
<td>23,000</td>
</tr>
<tr>
<td>University Contribution</td>
<td>-23,000</td>
</tr>
<tr>
<td>Technical Staff</td>
<td></td>
</tr>
<tr>
<td>28% 12 mos.</td>
<td>16,876</td>
</tr>
<tr>
<td>University Contribution</td>
<td>-16,707</td>
</tr>
<tr>
<td>Students</td>
<td></td>
</tr>
<tr>
<td>2 undergraduates</td>
<td>7,200</td>
</tr>
<tr>
<td>University Contribution</td>
<td>-7,200</td>
</tr>
<tr>
<td><strong>Total Salaries and Wages</strong></td>
<td>20,169</td>
</tr>
<tr>
<td>ITEM</td>
<td>2003</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td><strong>B. FRINGE BENEFITS</strong></td>
<td></td>
</tr>
<tr>
<td>Res. Assoc.:20.3%</td>
<td>4,060</td>
</tr>
<tr>
<td><em>University Contribution</em></td>
<td></td>
</tr>
<tr>
<td><strong>Total Fringe Benefits</strong></td>
<td>4,092</td>
</tr>
<tr>
<td><strong>C. EQUIPMENT</strong></td>
<td></td>
</tr>
<tr>
<td>Calorimeter Scintillator Testing Unit</td>
<td>20,000</td>
</tr>
<tr>
<td><em>University Contribution</em></td>
<td>-10,000</td>
</tr>
<tr>
<td><strong>Total Equipment</strong></td>
<td>10,000</td>
</tr>
<tr>
<td><strong>D. SUPPLIES AND MATERIALS</strong></td>
<td></td>
</tr>
<tr>
<td>Scintillator Plates, Cables,</td>
<td></td>
</tr>
<tr>
<td>Scintillating Fibers, Black Box,</td>
<td></td>
</tr>
<tr>
<td>Resistors, Capacitors</td>
<td>3,000</td>
</tr>
<tr>
<td>Other</td>
<td>1,000</td>
</tr>
<tr>
<td><strong>Total Supplies and Materials</strong></td>
<td>4,000</td>
</tr>
<tr>
<td><strong>E. TRAVEL</strong></td>
<td></td>
</tr>
<tr>
<td>Travel to American LC meetings</td>
<td>2,000</td>
</tr>
<tr>
<td><strong>Total Travel</strong></td>
<td>2,000</td>
</tr>
<tr>
<td><strong>F. TOTAL DIRECT COSTS</strong></td>
<td>40,261</td>
</tr>
<tr>
<td><strong>G. INDIRECT COSTS (On-Campus)</strong></td>
<td></td>
</tr>
<tr>
<td>On-Campus 47% of M.T.D.C.</td>
<td>14,223</td>
</tr>
<tr>
<td><strong>H. TOTAL COSTS (On-Campus)</strong></td>
<td>54,484</td>
</tr>
</tbody>
</table>
Bibliography


[3] We would like to thank Vladimir Issakov from the Brookhaven National Laboratories for a discussion on large area Avalanche Photo-diodes.
6.3. Fast Response Tile Scintillation Development for Calorimetry and Tracking in NLC Detectors (UCLC)

Calorimetry

Contact person: Dan Karmgard
e-mail: karmgard.1@nd.edu
phone: (574) 631-3362

Notre Dame

FY 2003: $44,410
FY 2004: $46,145
FY 2005: $78,322
Proposal to the University Consortium for a Linear Collider

August 23, 2002

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

Classification (accelerator/detector: subsystem)
Detector: Calorimetry/Tracking

Personnel and Institution(s) requesting funding
University of Notre Dame, Notre Dame, Indiana 46556

Contact Person
D. Karmgard
karmgard.1@nd.edu
(574)631-3362

Project Overview
Scintillation detection has a long history in particle physics. Scintillators are used for example in particle tracking and calorimetry (e.g., the D0 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 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 year’s 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

Because of the long-range of the Linear Collider Program, we are anxious to leverage on the QuarkNet program and draw in high school teachers and students (in the summer between their junior and senior years) to work on the project, under the supervision of an experienced technician and guided by part-time graduate students. This will afford a direct education/outreach component to the R and D program and will afford the teachers and students the opportunity to participate directly in the development of state-of-the-art new techniques for particle detection and measurement.

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.

Funds are requested for summer support of a high school teacher and two high school students. 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 $

Institution: University of Notre Dame

<table>
<thead>
<tr>
<th>Item</th>
<th>FY2003</th>
<th>FY2004</th>
<th>FY2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technician</td>
<td>19,200</td>
<td>19,700</td>
<td>40,700</td>
<td>79,600</td>
</tr>
<tr>
<td>HS Teacher</td>
<td>5,200</td>
<td>5,350</td>
<td>5,500</td>
<td>16,050</td>
</tr>
<tr>
<td>HS Students (2)</td>
<td>3,000</td>
<td>3,100</td>
<td>3,200</td>
<td>9,300</td>
</tr>
<tr>
<td>Travel</td>
<td>1,000</td>
<td>1,500</td>
<td>2,000</td>
<td>4,500</td>
</tr>
<tr>
<td>Equipment</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
<td>7,500</td>
</tr>
<tr>
<td>M&amp;S</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
<td>7,500</td>
</tr>
<tr>
<td>Indirect Costs</td>
<td>11,010</td>
<td>11,495</td>
<td>21,922</td>
<td>44,426</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>44,410</td>
<td>46,145</td>
<td>78,322</td>
<td>168,876</td>
</tr>
</tbody>
</table>
6.4. Exploring Crystal Calorimetry for A Linear Collider Detector (LCRD)

Calorimetry

Contact person: Usha Mallik
email: usha-mallik@uiowa.edu
phone: (319) 335-0499

Caltech
Iowa
South Carolina
SLAC
UT Austin

FY 2003: $53,805
Exploring Crystal Calorimetry for A Linear Collider Detector

Usha Mallik (The University of Iowa) [contact person],
Milind Purohit (University of South Carolina),
Jack Ritchie (University of Texas at Austin),
Rafe Schindler (SLAC), Ren-Yuan Zhu (Caltech)

August 28, 2002

1 Introduction

While there is a strong effort focusing on very compact sampling calorimetry for the future Linear Collider (LC) detector, we propose to explore crystal calorimetry with two kinds of heavy scintillating crystals, lead tungstate (PbWO₄) and LSO/GSO, for an electromagnetic calorimeter at the future linear collider.

Historically, total absorption crystal calorimetry has been a choice of precision electron and photon measurements, and we feel needs to be explored as an option for the electromagnetic calorimeter at the LC. Crystals usually have fast signal response to incident particles. They offer good electromagnetic energy resolution, which can be parametrized as $\frac{\sigma_E}{E} = \frac{\sigma_E}{\sqrt{E}} \oplus b\% \oplus \frac{c}{E}$ with $E$ in GeV, where $a$ is typically 1 or 2, $b$ can be controlled to 0.5 to 0.6%, and $c$ is 1 to 100 MeV, depending on the readout noise and crystal light yield. Crystal calorimeters made of heavy crystals with short radiation length and Moliere radius can be compact. They also offer good position resolution with appropriate lateral segmentation.
2 Crystal Investigation

Table 1 shows the choice of the crystals hitherto considered and their relevant properties, namely, radiation length ($X_0$), response time, Moliere radius, radiation hardness, density, cost, refractive index, interaction length and decay time.

<table>
<thead>
<tr>
<th>Properties</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BGO</th>
<th>PbWO$_4$:Y</th>
<th>GSO:Ce</th>
<th>LSO:Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_0$ (cm)</td>
<td>1.86</td>
<td>1.86</td>
<td>1.12</td>
<td>0.89</td>
<td>1.39</td>
<td>1.14</td>
</tr>
<tr>
<td>$R_{\text{Moliere}}$ (cm)</td>
<td>3.8</td>
<td>3.8</td>
<td>2.3</td>
<td>2.2</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Rad hard (Mrad)</td>
<td>0.01</td>
<td>0.01-0.1</td>
<td>0.1 - 1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>4.51</td>
<td>4.51</td>
<td>7.13</td>
<td>8.28</td>
<td>6.70</td>
<td>7.40</td>
</tr>
<tr>
<td>Cost ($/cc)</td>
<td>3.2</td>
<td>4</td>
<td>4</td>
<td>2.5</td>
<td>see text</td>
<td>see text</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.79</td>
<td>1.95</td>
<td>2.15</td>
<td>2.20</td>
<td>1.85</td>
<td>1.82</td>
</tr>
<tr>
<td>Int.length$\lambda$ (cm)</td>
<td>37</td>
<td>37</td>
<td>21.8</td>
<td>18</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>680</td>
<td>16</td>
<td>300</td>
<td>5</td>
<td>56</td>
<td>47</td>
</tr>
<tr>
<td>(slow component)</td>
<td>3340</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The reason for our choices are clear from the table. Initial tests will be performed with one or two crystals in the lab bench test, using various read-out devices, e.g., Avalanche Photo-diodes (APD), large-area photo-diodes, PMT's, and, vacuum photo-triodes (VPT). The PMT's will be used only in the bench test, since they will not work in high magnetic fields. The APD's are ideal for this and for radiation hardness. The bench test will measure number of photo-electrons detected per MeV, and corresponding photon/MeV yield for the crystal. We will also investigate the uniformity of the crystals.

2.1 PbWO$_4$

The Yttrium doped lead tungstate crystals, used by the CMS experiment at LHC, are mass produced by Bogoroditsk Techno-Chemical Plant in Russia and Shanghai Institute of Ceramics (SIC) in China. They are available at low cost, typically 2.5 to 3 $/cc in large quantity. It, however, has low light yield as shown in Table 1. Using different dopants, SIC has increased the photon yield tenfold mainly in the $\mu$s decay component without altering other
properties. In addition, these PbWO₄ crystals still have a fast component with \( \sim 10 \) ns decay time.

We will investigate the light yield of both Yttrium doped PbWO₄ crystals and the PbWO₄ crystals with high light yield from SIC. Evaluation will also be made to see if the fast component provides sufficient photons, e.g. for energy measurement or for triggering, and if the signal over the background is sufficient for the LC physics by using either the fast component or the sum of the two components. The light yield for both the fast and the slow components will be measured with various readout devices. The light yield and response uniformities and the linearity will also be measured to see if they are in the accessible range. Photo-electron collection at both the near and the far face will also be measured to study the propagation of the signal in the crystal. In a longer term we would test the response of the crystals with a beam, where the linearity of response over a large range can really be tested. It would be desirable to acquire a 5 \( \times \) 5 crystal matrix for the beam test.

We will use Yttrium doped lead tungstate of the kind used by CMS, and the two kinds of high-photon-yield types produced by SIC. The latter is not yet available commercially, but may be obtained by one of us, Ren-Yuan Zhu, who has an R&D contract with the SIC. He expects to obtain high quality Yttrium doped PbWO₄ samples about three months after the order is placed. We plan to procure two crystals (of each type) of \( \sim 1.2 - 1.3 \) Moliere radii square surface and \( \sim 25 \) radiation lengths depth.

### 2.2 LSO:Ce/GSO:Ce

Cerium doped LSO and GSO are also potentially very desirable crystals. They are mainly used in small size in medical applications, so are expensive commercially. The expected cost for large size LSO is $50/cc. The LSO:Ce is produced only by CTI, a company that produces PET scattering by using LSO:Ce and BGO, while the GSO:Ce is produced by Hitachi. As seen from Table 1, both LSO:Ce and GSO:Ce have very high light yield, short radiation length and small Moliere radius etc. The cost of LSO:Ce and GSO:Ce, however, may be significantly reduced if they are mass produced for high energy and nuclear physics applications. Historically, initial high crystal costs at the R&D stage were substantially reduced as improvements were made in production in large quantities. It is not unlikely that in the future, the cost of production for these crystals will also decrease substantially. As with
PbWO₄, similar bench tests need to be performed; uniformity study and signal propagation studies are very important.

3 Simulation

A critical part of this R &D program is a substantial simulation effort, especially, to check what sort of longitudinal segmentation is needed for an adequate energy flow algorithm to succeed. The Energy Flow concept to improve jet measurements is an important aspect of calorimetry at the LC. This is interconnected with the physics processes to be studied at the LC, the jet reconstruction algorithms to be used, and resolution that can be achieved at the LC energies with a typical LC detector. It is a non-trivial question that must be thoroughly explored as part of designing this system, central to the LC detector. In fact, just how the trade-off between e/h ratio and resolution/segmentation play in energy flow needs to be addressed. We are interested in two main issues concerning the application of the energy flow: one is the physics limitations to the jet resolution and the other is how the longitudinal segmentation might help in improving jet resolution. Zhu is particularly interested in studying the effects of jet resolution from perturbative QCD as well as from fragmentation. Some discussions have already been initiated with the simulation group at SLAC.

Another aspect of our plan is to simulate the crystal response properly based on the bench test data. The bench tests performed in the lab will provide adequate information to crudely model the crystal behavior. The beam test, however, will provide the final and more accurate details. With the data from the bench test, we will study various types of segmentation for the full calorimeter with the full detector Monte Carlo.

The beam test will allow us to verify the simulation of the crystal behavior in detail. Once this is achieved, we can then test various segmentation schemes, especially longitudinally, to iterate and obtain a realistic the energy flow measurement. At this stage, various calorimeter parameters need to be optimized in the full detector Monte Carlo and necessary resolution for various physics processes checked with better accuracy. This, along with a cost estimate will constitute a very important part of the study to determine the final choice for the calorimeter.
4 Deliverables and Resources

The goal for the first year is to start the canonical LC detector simulation with a crystal EM calorimeter with a realistic resolution to study some of the benchmark physics processes in and out of a jet environment. This will, hopefully lead to understanding the dependencies of resolution on various parameters like lateral and longitudinal segmentations, and also what kind of HCAL or tracking performance is necessary. The need or lack thereof of realtive responses of the CAL to electromagnetic and hadronic showers will be explored. An Iowa postdoc will carry out a major part of the simulation study.

On another front we will test the light yield for the three types of PbWO$_4$ crystals with various readout schemes (mainly PMT’s initially), including fast and slow responses of the two high-photon-yield types. Also measure signal propagation through the crystal by observing the difference in responses with readout attached to the front and then in the back side of the crystals. Next we would like to test the uniformity of response, along with the energy division between two adjacent crystals.

Not all of the above might get completed in one year, in fact, some of the studies will be iterative, but, we should have a firm foothold on many of these issues. They need to be done. Most of the proponents are collaborators in BABAR, and therefore maintain close contact. Jack Ritchie is presently involved in the BABAR (CsI) calorimeter, the construction of which was led by Rafe Schindler and Bill Wisniewski. Schindler will provide lab space and any incidental technician help when needed. Usha Mallik will provide two graduate students, and Milind Purohit and Sridhara Dasu (Wisconsin) will provide a graduate student each to carry out these tests with regular supervision by Mallik. Dasu is committed to CMS in addition to BABAR, and therefore will not participate in the proposal. Zhu will provide his expertise along with procuring the crystals. Local supervision will be provided by Schindler, and to some extent by Bill Wisniewski from SLAC. Because of his new role as the Technical Coordinator of BABAR, he will be available in an advisory role only.
5 Long Term Goal

This program in FY03, hopefully, is the beginning of a long term project aiming at building a crystal calorimeter for the linear collider. As mentioned earlier, the next step to the FY03 program is to test the crystals in a beam with a crystal matrix, with and without longitudinal segmentation. The beam test results with a prototype crystal matrix together with the Physics and detector simulations will help to establish the feasibility of an electromagnetic crystal calorimeter at the linear collider.

6 FY03 Budget

A total of $53,805 is requested to cover the FY03 cost including the indirect cost (none on the equipment). Table 2 lists the break down of the budget. Two of each kind of PbWO₄ crystals are to be procured. Because of the high cost, we will try only one crystal of LSO:Ce or GSO:Ce with the volume of ~250cc.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost in $</th>
<th>Final Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbWO₄</td>
<td>six</td>
<td>5,000</td>
<td>5,000</td>
</tr>
<tr>
<td>LSO:Ce or GSO:Ce</td>
<td>one</td>
<td>15,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Readout Electronics</td>
<td>APD, PMT etc</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Travel</td>
<td>To Caltech and back</td>
<td>3,000</td>
<td>3,765</td>
</tr>
<tr>
<td>0.5 supplement</td>
<td>two</td>
<td>16,000</td>
<td>20,040</td>
</tr>
<tr>
<td>Total</td>
<td>One year R&amp;D</td>
<td>49,000</td>
<td>53,805</td>
</tr>
</tbody>
</table>

To read out the lead tungstate with sources we need high gain PMTs, hence two Hamamatsu R2259 will be used in addition to two APD’s, 2cm × 2cm photo-diodes, and VPT’s. Along with the associated electronics we estimate $10,000 for all readout components. For the two students from South Carolina and Iowa, a supplemental equivalent for each student to be resident at SLAC is added. The Iowa postdoc is paid from the base funding, and is not included here. A small amount of $3,000 for travel between Caltech and
SLAC (or Iowa or South Carolina) is added. The indirect cost for South Carolina is 25% and for Iowa is 25.5% (off-campus rate) on support and travel. One of us, Jack Ritchie, is not asking for any funds in the first year; also, it is possible that other faculty members from UT Austin may join this R&D effort in the future. Rafe Schindler and any other participation from SLAC in this R&D will be funded by the lab.
6.5. Development of a silicon-tungsten test module for an electromagnetic calorimeter (LCRD)

Calorimetry

Contact person: Raymond Frey
email: rayfrey@cosmic.uoregon.edu
phone: (541) 346-5873

Oregon
SLAC

FY 2003: $37,500
Project name

Development of a silicon-tungsten test module for an electromagnetic calorimeter

Classification (accelerator/detector:subsystem)

Detector: calorimetry

Institution(s) and personnel

University of Oregon, Department of Physics and Oregon Center for HEP:
Raymond Frey (professor), David Strom (professor)

Stanford Linear Accelerator Center:
M. Breidenbach (faculty), D. Freytag, N. Graf, G. Haller, J. Jaros (faculty), M. Huffer, J.J. Russell

Contact person

Raymond Frey
rayfrey@cosmic.uoregon.edu
(541) 346-5873

Project Overview

The TESLA and SD detector designs call for a silicon-tungsten electromagnetic calorimeter (ECal) as the best option for providing the necessary segmentation to implement the energy flow method for jet reconstruction at the LC, capable of achieving jet energy resolution of $\approx 0.3/\sqrt{E_{\text{jet}}}$, as recommended by LC physics studies. The number of detector pixels for these ECal designs is on order 50 million. One of the outstanding technical questions is how to integrate a silicon detector wafer with its readout electronics. Along with the cost of the silicon detectors themselves, a solution to the integration issue is likely to determine the overall viability of the silicon-tungsten approach. We have, in fact, proposed $^1,^2$ a possible solution to the integration problem. We propose to implement this idea in stages, starting with component feasibility assessments (year 1) and engineering prototypes (year 2). If successful, we plan to develop a full ECal module (year 3) for testing in a beam.

Briefly, we hope to integrate detector pixels on a large, commercially feasible silicon wafer. For example, a 6 inch wafer would include on order 1000 pixels for pixel size 5x5 mm$^2$. One readout chip for each wafer would be bump bonded to the wafer. The chip would include the analog and digitization elements for the 1000 pixels. In this way, the channel count is effectively reduced by a factor 1000. We take advantage of the low beam duty cycle ($5 \times 10^{-5}$ for NLC) to reduce the heat load using power cycling. Initially, we break up the project into two areas of responsibility:

1. Silicon detector design, procurement, and characterization (Oregon)

2. Readout chip design, procurement, and testing (SLAC)
The description above is the main thrust of this proposal. However, several of us (Frey and Strom at Oregon, Graf and Jaros at SLAC) also plan to be involved in closely related simulation and software activities, for which we are not requesting funding:

- **Technical simulations.** Use EGS4 and Geant4 to study dynamic range, longitudinal sampling optimization, segmentation, etc. Graf is developing a general package for test beam configuration simulation to be used by other groups as well as ours. Use SPICE to study issues like crosstalk from pixels to metallization traces on the wafers.

- **Detector modeling simulations.** Continue to use the LCD software packages to optimize detector configurations as a function, for example, of photon and tau reconstruction performance, pion rejection, etc, as well as performance for benchmark physics processes. The LCD Geant4 packages are to be used for this.

- **Algorithm development.** The Energy Flow (EF) concept is to be used for jet reconstruction. In large part this is what underlies the detector concept. There are many different ideas for how to implement EF algorithmically. We plan to continue these studies. We are included in a separate proposal, submitted by NIU/NICADD, for this element of research, although no funding is requested by us at this time.

- **Physics simulations.** Help to develop multi-jet and other benchmark processes to be used for Energy Flow evaluation. Study the contributions to jet resolution from the detector, QCD, 2-photon backgrounds, etc. Studies to date indicate that, unlike for the LHC, the resolution is limited by the detector, not QCD and backgrounds. We would like to explore this further.

**Some details on the silicon detector research**

Several experts on silicon detector fabrication are projecting that the cost for simple silicon detectors, like those considered here, will be in the range 1 to 2$/cm^2 when detectors are purchased on a large scale. The current SD design calls for 13x10^6 cm^2 of silicon. With silicon being the largest cost component, it seems that a reasonable total cost for the silicon-tungsten ECal is achievable. However, to keep the silicon cost at this level requires that the silicon layout be as simple as possible. Therefore, we seek to use DC-coupled detectors if possible. High resistivity silicon (∼10 kΩ-cm) should initially have low leakage currents at full depletion (∼1 nA or less per pixel), and our initial studies of potential radiation damage indicate that this current will not increase substantially. This allows DC-coupled detectors to be used with standard readout electronics with a front-end similar to the AMPLEX chip used by the silicon-tungsten luminosity calorimeters at LEP.

Since Energy Flow performance is best when individual particles can be separated in the calorimeter, a small Moliere radius in the ECal is highly desirable. Tungsten, with R_m=9 mm, provides this. However, the effective Moliere radius includes the sampling layers. For example, for tungsten layers of thickness 2.5 mm (as for SD), the effective Moliere
radius becomes \((9 \text{ mm})(1 + z/2.5)\), where \(z\) is the thickness of the sampling layer (i.e. everything not tungsten) in mm. So, one of our design goals is to keep \(z\) small.

Thermal issues are important for most calorimeters, especially as in our case with embedded electronics. Since we aim to put all electronics for each \(\sim 10^3\) pixels on a single readout chip (ROC) within the detector, this is a concern. Here, we use one of the nice features of LC design — the bunch structure. For NLC the bunch-train duty cycle is just \(5 \times 10^{-5}\). So one might hope to use power pulsing to keep the electronics off for most of the dead time. If one assumes a power duty cycle of \(10^{-3}\), then the average power consumption of the ROC will be small (\(\sim 1\text{mW}\)) and hopefully manageable with simple techniques. Clearly, it is important to demonstrate this.

Current status

We are presently working with potential vendors of the silicon detectors on detector design, layouts, etc. We (Oregon) expect to buy prototype detectors as soon as funds become available. Meanwhile, the SLAC group is working on the readout chip design. We have begun weekly SLAC-Oregon phone meetings. We have discussed our design ideas at regional and international meetings, and it seems that other groups, including those primarily studying TESLA, will be interested in the results of this work.

Description of first year project activities

Design and procure first round of detector prototypes. We do not yet know the prototype costs, but based on past experience we hope to purchase about 5 detector wafers with the indicated budget line. These are to be full 6 inch wafers with pixels, traces, bump bond pads, biasing, etc. These are to be received at Oregon and will undergo initial testing, including basic QA and crosstalk measurements (using an IR laser system). The tests will include leakage current, capacitance, and depletion voltage measurements. In parallel, SLAC will develop the first readout chip. No funds are requested for this part. The goal is to have wafers and readout chip ready to be bonded together for testing by end of year one. Year one is to include a silicon detector test in a 5 T magnetic field. We now also include 2.5 k\$ for travel to cover 1) the Oregon part of the simulation effort, and 2) the planned meetings with European colleagues to discuss our silicon-tungsten work. We expect to include meetings at SLAC as part of our ordinary SLAC travel for BaBar, so do not request funding for this.

Deliverables include the prototype detectors and first bench test results, a first readout chip design, and delivery of the first chips.
**Budget**

<table>
<thead>
<tr>
<th>Institution</th>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>Custom silicon detector prototypes (about 5)</td>
<td>$25,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Probe and test equipment for detectors</td>
<td>$10,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Travel</td>
<td>$ 2,500</td>
</tr>
<tr>
<td>Oregon</td>
<td>Oregon total</td>
<td>$37,500</td>
</tr>
<tr>
<td>SLAC</td>
<td>SLAC total</td>
<td>$0</td>
</tr>
</tbody>
</table>

Notes: Indirect costs for the travel are included in the 2.5 k$. We have a clean room at Oregon for the detector work, and a probe station, but not all of the required test equipment.

**Description of second year project activities (guesstimates)**

Note: Year 2 and 3 activities are necessarily vague at this point. Test the first round of prototypes using various particle sources on the bench. Most likely will need a second round of detector (and readout chip) prototypes. Perform the next level of system measurements for the final design, such as heat dissipation, leakage current changes with radiation, signal size, crosstalk, noise, etc. Start to design a mechanical system for a full test beam experiment. Collaborate with others on the beam test, hopefully including a hadron calorimeter prototype.

<table>
<thead>
<tr>
<th>Institution</th>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>Custom silicon detector prototypes – round 2</td>
<td>$25,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Data acquisition equipment</td>
<td>$10,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Test equipment</td>
<td>$ 5,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Travel</td>
<td>$ 5,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Oregon total</td>
<td>$45,000</td>
</tr>
<tr>
<td>SLAC</td>
<td>SLAC total</td>
<td>$0</td>
</tr>
</tbody>
</table>

**Description of third year project activities (guesstimates)**

Procure a “final” set of detectors. At this point, the cost/detector will be reduced, based on past experience. Goal is to build a full-depth ECal module of 30 layers (wafers), one wafer wide. The tungsten radiator plates to be procured and fabricated by method to be determined. Test beam to include both EM particles and hadrons. Other detector modules hopefully to be included (i.e. HCal, tracker) if possible, to be determined.
## Year 3

<table>
<thead>
<tr>
<th>Institution</th>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>Custom silicon detector prototypes (25-30)</td>
<td>$40,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Tungsten, material and machining</td>
<td>$40,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>Oregon total</td>
<td>$80,000</td>
</tr>
<tr>
<td>SLAC</td>
<td>SLAC total</td>
<td>$0</td>
</tr>
</tbody>
</table>

## References


## Relevant experience of proponents

The SLAC group has vast experience in design of $e^+e^-$ detectors, including design and implementation of the readout electronics for most major detector systems for the SLD detector and several BaBar sub-systems. Of specific relevance, recently members of the group led the design of the electronics for the silicon strip detectors for the GLAST experiment. Graf is co-leader of the American Linear Collider Physics Group (ALCPG) simulations group and is the leader of the SLAC group which is developing the LCD simulation software.

Strom and Frey have each worked on silicon-tungsten luminosity calorimeters for OPAL (Strom) and SLD (Frey). Strom in particular was a key person in the OPAL silicon-tungsten development. Frey is co-leader of the ALCPG calorimeter group. Frey and Iwasaki (former postdoc, now at U. Tokyo) have done extensive calorimeter simulation work, which has been reported at many LC meetings.
6.6. Digital Hadron Calorimetry for the Linear Collider using GEM technology (LCRD)

Calorimetry

Contact person: Andy White
email: awhite@uta.edu
phone: (817) 272-2812

Argonne
Northern Illinois
UT Arlington

FY 2003: $72,641
Digital Hadron Calorimetry for the Linear Collider using GEM Technology

University of Texas at Arlington

Andrew Brandt, Kaushik De, Shahnoor Habib, Venkat Kaushik, Jia Li, Mark Sosebee, Andy White*1, Jae Yu*2
1 GEM detector contact: awhite@uta.edu, (817) 272-2812 (office), (817) 272-2824 (FAX)
2 Simulation contact: yu@fnal.gov, (817) 272-2814 (office), (817) 272-2824 (FAX)

Collaborators
D. Chakraborty et al., NICADD/ Northern Illinois University
S. Magill et al., Argonne National Laboratory

Overview of Project
The UTA group proposes research and development of digital hadron calorimetry using Gas Electron Multiplier (GEM) technology for the sensitive gaps. We plan to construct prototypes to understand the characteristics of GEM and its operation in the first year of the proposal. We plan to construct simulation packages that implement GEM based digital hadron calorimetry. We also plan to contribute to development of energy flow and calorimeter tracking algorithms, in collaboration with Northern Illinois University and Argonne National Laboratory teams.

Digital Hadron Calorimeter

Digital hadron calorimetry holds significant promise for achieving the excellent energy resolution required at a linear collider, while containing subsystem costs at a manageable level. By using small calorimeter cells, typically a few cm², it is possible to track charged particles in the calorimeter and associate energy deposits with the corresponding tracks whose momenta are measured in the tracking system. After removal of this “charged energy”, the remaining neutral energy is measured using the digital information from the neutral clusters (those without associated incoming charged track(s)). Current estimates indicate that an overall hadronic (jet) energy resolution of $30\%/\sqrt{E}$ should be achievable, using a digital hadron calorimetry along with an energy flow algorithm. An example of the need for this precision is the reconstruction of W and Z bosons from their hadronic decays. The fine granularity required for a digital hadron calorimeter also allows for separation of W and Z bosons in the interactions.

Development of GEM-based Digital Hadron Calorimetry

The best technology for implementing digital hadron calorimetry remains an open question. The essential requirements include:
- a robust design with stable, reliable operation
- a thin sensitive layer for compact calorimeter design
- on-board amplification/discrimination/digitization for digital readout
- high efficiency for minimum ionizing particle (MIP) tracking in a hadron calorimeter
- flexible design for implementation of varying cell sizes
in addition to the basic requirements of minimal supports/intrusions for hermeticity, ease of construction, and cost containment.

To satisfy these requirements we are exploring an implementation based on the Gas Electron Multiplier (GEM) technology developed at CERN by Fabio Sauli and the GDD Group\(^1\). As shown in the schematic in Figure 1, GEM active layers are alternated with layers of absorber to form a sampling calorimeter.

The GEM layer is 6mm thick with a small amount of space for an electronics layer containing a charge amplifier, discriminator, and register. It may be useful to have two levels of discrimination – one for tracking single MIPs, and one for multiple tracks. The GEM approach allows great flexibility in the cell design; limited only by the cost of the readout, a large range of sizes is possible from microstrips through macroscopic pads. This would allow, for instance, the inclusion of a number of precision layers in the calorimeter stack if it proved useful, for example for muon tracking. One can also imagine that future improvements to a significantly finer granularity by implementing finer readout pads ganged, initially, to a larger pad sizes.

It is highly desirable to transport digital signals from the calorimeter, rather than small analog signals. However, this requires careful design and placement of the onboard electronics to satisfy constraints of space, reliability, heat load, and cost. We might anticipate having GEM calorimeter active modules with perhaps O(200) channels per module. One approach to the readout would then be to have a small number of ASIC’s per module distributed along the module center line. Each channel of an ASIC would comprise a charge amplifier, discriminator, and register. An example of a device with low power/channel (~1 mW/channel) is that developed for the CMS tracker and adapted for the triple GEM tracker for the COMPASS experiment\(^2\). Our goal is to have the electronics “layer” not make a significant contribution to the overall thickness of the

---

**Figure 1.** A schematic diagram of a digital hadron calorimeter using triple GEM sampling layers
active layer. Beyond these considerations, we are looking at the use of regional collectors/concentrators to accumulate and pass on the digital signal information to the DAQ system.

We have begun working on a first GEM prototype to give us construction and operational experience with this technology. Figure 2 shows a drawing of the first prototype, and the photograph shows the body and readout pad layer of the prototype. The first set of four GEM foils of size 10cmx10cm has been purchased from the GDD group at CERN. This prototype can be configured as a single, double, or triple GEM detector. It will allow us to understand the signal characteristics and their dependence on the potential differences across the drift, transfer, and induction gaps of the GEM, and the signal characteristics from discharges.

Subsequently, we plan to design and build prototype GEM calorimeter modules with appropriate designs for signal readout with noise shielding, module-to-module interconnections for power in and signals out, and spacers between large GEM foils to prevent discharges from spiraling low energy charged particles in the magnetic field. This will also require us to develop our own techniques for producing GEM foils of the size needed for calorimetry, with an eye towards future mass production of foils. In this connection, we note that there are several U.S. groups interested in GEM foil production for tracking applications. We have made initial contacts with these groups and anticipate that this may lead to a coherent U.S. effort to produce foils. Finally, after successful operation of prototype modules, we will design and build a calorimeter stack for trials with cosmic rays, and in a test beam.

**Detector Simulation and Algorithm Development**

The UTA group is in the process of setting up various Monte Carlo simulations tools for detailed studies of digital hadron calorimetry. We have made Pandora-Pythia\(^3\) to provide ASCII HEPEvt output format to input to Geant4 tools. We have successfully implemented Mokka\(^4\) as our simulation tool. Among many issues that need to be addressed and studied in depth, the most urgent and important issue are the discharge characteristics of the GEM detectors. Since the digital hadron calorimeter we plan to
employ consists of multiple GEM layers to increase gain, it is crucial for us to understand what the expected ion-electron pair density is for high energy, multi-jet events, such as \( \text{WW or ZZ} \rightarrow 4\text{jets} \), resulting from \( e^+e^- \) collisions at various center-of-mass energies. Since this study does not depend on the detailed detector geometry, other than the absorber material and the sensitive gap sizes, we are working on analyzing multi-jet data, generated locally using Mokka. We also plan to work with the SLAC team to use the events that have been generated there for Linear Collider studies.

In the mean time, in order to perform more realistic and detailed studies, we will implement GEM geometry for prototypes to be built at UTA into the MC. Upon the success of the prototype geometry, we will expand the geometry to replace the existing sensitive gaps for larger scale studies in energy flow and calorimeter tracking algorithms. An example of the detailed studies is the use of spacers to minimize fake signals caused by low energy electrons spiraling down the sensitive gas gap.

Since the resolution enhancement of digital hadron calorimeters will only work when assisted by a well-developed energy flow algorithm, development of such algorithms is going to be another focus of our efforts. The primary issues we will concentrate on are:

- Optimal granularity of the readout cells to keep the linearity of the calorimeter response and to allow efficient removal of the showers associated with charged hadrons
- Sampling fraction for optimal energy resolution
- Charged track and calorimeter shower matching for shower removal
- Dependence of the energy resolution and linearity on electromagnetic fraction of the jet
- Determination of thresholds for optimal noise reduction and occupancy, retaining minimum ionizing particle signal identification.
- Impact of mechanical support structures for GEM layers and spacers
- Optimal spacer distances to minimize fake signal without degrading energy or position resolution
- Issues specific to GEM

Undoubtedly, development of optimal energy flow and calorimeter tracking algorithms will take time and will continue beyond the first year of the project.

The UTA team has been working with Northern Illinois University (NIU) and Argonne National Laboratory (ANL) teams on simulation and energy flow algorithm development effort since January, 2002. The NIU and ANL teams have submitted a combined proposal independently as part of the UCLC proposal. The three teams are planning to continue working together on simulation resource sharing, development of simulation packages and algorithms for energy flow and calorimeter tracking.

**Future Plans**

In subsequent years, we plan to construct a multiple layer digital hadron calorimeter module and to take cosmic ray data to understand the operation and responses of the detector. We intend to use cosmic ray data for further development of calorimeter tracking algorithms. Subsequently, we also plan to participate in test beam activity. We anticipate that the simulation package and algorithm development will continue through the subsequent years, along with cosmic ray and test beam data analyses.
Facilities and Resources
The UTA High Energy Physics group has a 10,000 sq. ft. detector development facility which has recently been used to produce the Intermediate Tile Calorimeter for ATLAS, and to build the upgrade Intercryostat Detector, and Forward Proton Detector for D0. We also have high-grade clean rooms at our NanoFabrication facility. For simulation work we have a farm of 50 processors and anticipate substantially greater computing resources in the near future.

Budget
During the first year we anticipate building the first GEM prototype, investigating GEM foil production locally, and building one or more prototype GEM calorimeter layer module(s). In addition, we need support for a graduate student for simulation, algorithm development, and MC data analyses. We are therefore requesting support for the items listed in Table 1 during the first year. For the second and third years, when construction and testing of a medium sized calorimeter stack for cosmic ray testing and for test beam will occur, we anticipate needing support of $150,000 per year.

Table 1. Detailed cost estimate for the first year GEM prototype project

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials and workshop time for first prototype and GEM calorimeter layer prototype</td>
<td>$25,000</td>
</tr>
<tr>
<td>Charge preamplifier units</td>
<td>$6,000</td>
</tr>
<tr>
<td>ADC for signal characterization</td>
<td>$3,500</td>
</tr>
<tr>
<td>Gas system</td>
<td>$2,500</td>
</tr>
<tr>
<td>Trigger scintillators, PMT’s and electronics</td>
<td>$4,000</td>
</tr>
<tr>
<td>Investigation of GEM foil production, trials with local industry</td>
<td>$5,000</td>
</tr>
<tr>
<td>PC for data collection</td>
<td>$1,000</td>
</tr>
<tr>
<td>0.5 graduate student support for simulation and algorithm development, including fringe</td>
<td>$12,325</td>
</tr>
<tr>
<td>Travel to LC calorimeter meetings and workshop(s)</td>
<td>$5,000</td>
</tr>
<tr>
<td>Indirect cost</td>
<td>$8,316</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$72,641</strong></td>
</tr>
</tbody>
</table>

References:

1) [http://gdd.web.cern.ch/GDD/](http://gdd.web.cern.ch/GDD/)
2) C. Altunbas et al. NIM A490 (2002) 177-203
6.9. Development of energy-flow algorithms, simulation, and other software for the LC detector (UCLC)

Calorimetry

Contact person: Dhiman Chakraborty  
email: dhiman@fnal.gov  
phone: (630) 840-8569

NIU

FY 2003: $45,400  
FY 2004: $96,500  
FY 2005: $144,700
Proposal to the University Consortium for a Linear Collider

September 6, 2002

Proposal Name
Development of energy-flow algorithms, simulation, and other software for the LC detector.

Classification (accelerator/detector: subsystem)
Calorimeter (+ tracker): simulation, software, and algorithm development.

Personnel and Institution(s) requesting funding
M. Arov, G. Blazey, D. Chakraborty, A. Maciel, M. Martin, R. McIntosh, 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,
N. Varelas et al., University of Illinois at Chicago,
J. Butler et al., Boston University.

Contact Person
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 energy-flow algorithms (EFA, see below). Simulations/algorithms 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 to a precision of $\sim 3$ GeV, or,
in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ ($E$ in GeV), something yet to be achieved in any
existing calorimeter. Similar precision in measurements of jet and missing energy 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
calorimeters working in tandem with the tracking system at the LC which will necessarily require the
development of new algorithms and technology in this sphere.

The most promising means to achieving such unprecedented resolutions at the next linear collider is
through energy flow algorithms (EFA) which seek to separate and measure in a jet clusters of energy
initiated by neutral hadrons, carrying, on average, only $\sim 11\%$ of a jet’s total energy. 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 EFAs must be finely segmented both transversely and longitudinally for 3-D
shower reconstruction, so hits initiated by charged particles can be separated from those initiated by
neutral particles by associating the former to corresponding tracks found in the inner tracking volume.
This requires a realistic simulation of both the physics processes and the shower development that
occurs in materials. The design optimization requires the simulation, graphics, 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. Much of the physics in question is beyond the SM, requiring
simultaneous coverage of broad ranges of undetermined parameters. Parametrized fast simulation
programs will thus have to be developed once the algorithms have been stabilized. Parametrization of
EFAs 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 (the Argonne
National Laboratory) began collaborating on EFAs, 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, the ECFA/DESY meeting at St. Malo, the American LC
workshop in Santa Cruz, and at the International LC Physics and Detector Workshop in Korea.

Towards 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 energy fluctuations in a hadronic shower. Three independent approaches to the implementation
of an EFA 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. NIU 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 dimensions and
particle types. The ANL team has used a standalone GEANT3 program for limited tests of
geometries that have yet to be supported in the above environment. 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:** This can also be changed in JAS (within
certain limits that we are working to remove). We plan to optimize the 3-D granularity of cells for
the most promising EFAs 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, . . . . The basic performance measure here is the ability to separate showers from charged and neutral hadrons - the key to any EFA.

**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.

**Energy-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 EFA will play a key role in the ultimate achievement of the best jet energy resolution. As a first step, we plan to implement an EFA 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 this project 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 package derives much from the LCDRoot package, but not its dependence on ROOT. The new package, yet to be named, fully complies with the model specifications put forth by the simulation group. Most importantly, the detector description is specified at run-time through an XML interface, and the output is available in both the standard sio format as well as root files. 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.

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 SLAC, U. of Chicago, and several other institutions. A workshop is being planned at NIU/NICADD in October, 2002, to bring the groups together to get up to speed, identify an agenda, and set out in an organized manner.

Activities outlined in this proposal are 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.

**FY2003 activities and deliverables**
During the first year we will concentrate on the development of EFAs 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 class of full-fledged energy flow algorithm based on full simulation and reconstruction of the calorimeter and the tracking system. 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.

**FY2004 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 EFAs. The second year deliverables will be a quantified assessment of physics reach vs calorimeter performance for the Linear Collider including comparisons between digital and analog options for the hadronic calorimeter.

**FY2005 activities and deliverables**
In the third year we will embark on the development of parameterized simulations of the energy 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 EFAs.

**Three-year budget, in then-year K$**

<table>
<thead>
<tr>
<th>Item</th>
<th>FY2003</th>
<th>FY2004</th>
<th>FY2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>0</td>
<td>21.0</td>
<td>44.0</td>
<td>65.0</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>27.5</td>
<td>29.5</td>
<td>30.5</td>
<td>87.5</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Salaries and Wages</strong></td>
<td>27.5</td>
<td>50.5</td>
<td>74.5</td>
<td>152.5</td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>0</td>
<td>8.5</td>
<td>18.0</td>
<td>26.5</td>
</tr>
<tr>
<td><strong>Total Salaries, Wages and Fringe Benefits</strong></td>
<td>27.5</td>
<td>59.0</td>
<td>92.5</td>
<td>179.0</td>
</tr>
<tr>
<td>Equipment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Travel</td>
<td>4.0</td>
<td>8.0</td>
<td>8.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total direct costs</strong></td>
<td>31.5</td>
<td>67.0</td>
<td>100.5</td>
<td>198.0</td>
</tr>
<tr>
<td>Indirect costs (44% of non-equipment)</td>
<td>13.9</td>
<td>29.5</td>
<td>44.2</td>
<td>87.6</td>
</tr>
<tr>
<td><strong>Total direct and indirect costs</strong></td>
<td>45.4</td>
<td>96.5</td>
<td>144.7</td>
<td>285.6</td>
</tr>
</tbody>
</table>

**Budget justification**
The first year’s activities revolve around the development of energy flow algorithms. This will involve NICADD and ANL physicists (not included in the budget shown here) and 1.5 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 1/2 post-doc with additional support from NICADD and ANL. During the third year, the development of parameterized simulations will be supported by a post-doc, together with 1.5 FTE graduate students.

**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-node Fermilab Linux farm (run by NIU personnel), open to expansion as the need arises.
6.10. Investigation and Design Optimization of a Compact Sampling Electro-magnetic Calorimeter with High Spatial, Timing and Energy Resolution (UCLC)

Calorimetry

Contact person: Graham Wilson
email: gwwilson@ku.edu
phone: (785) 864-5231

Kansas

FY 2003: $49,000
FY 2004: $124,000
FY 2005: $195,000
6.10.2

Proposal to the
University Consortium for a Linear Collider

September 3, 2002

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

Classification (accelerator/detector: subsystem)
Detector: electromagnetic calorimetry (barrel, endcap, low-angle).

Personnel and Institution(s) requesting finding
Philip S. Baringer, Alice Bean, David Z. Besson, Darius Gallagher and Graham W. Wilson, Dept. of
Physics and Astronomy, University of Kansas, Lawrence, KS 66045.

Collaborators
There are a number of people working on related topics whom we would expect to be able to collaborate
well with - but at the moment no formal collaboration exists.
The University of Colorado group (U. Nauenberg - contact person) are engaged in related activities
for scintillator calorimetry and are discussing collaborating.
We also anticipate benefiting from on-going simulation infrastructure efforts presently supported or
contributed to by SLAC, ANL and NIU and collaborating with individuals at those institutions.

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

Project Overview
Motivation: Existing linear collider (LC) detector designs emphasise precision tracking of charged
particles ($\sigma(p_T) \approx 5 \times 10^{-3} \text{GeV}^{-1}$) 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, 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) ECAL’s 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 sacrifice time resolution for 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 (e.g. 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 calorimeter 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 (e.g. 40 as in [3]) and Lead-Scintillator sandwiches such as the Shashlik 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.

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 (e.g. 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

---

1Note 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).

the light with minimum dead space would be 5 cm × 5 cm × 1 mm scintillating tiles with primary square cross-section (1 mm × 1 mm) WLS fibers coupled to some or all of the 4 tile edges. Up to four additional secondary (1 mm × 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 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.

Personnel

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

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 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. 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.

We have recently opened a post-doctoral researcher position for search. Contingent on finding a well suited candidate, we envisage that this person would spend 0.5 FTE on this project.

FY2003 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 that will be investigated are single particle energy, angular and directional resolution vs energy, photon-pion separation vs energy and time resolution. We intend to do these studies with a full MC shower simulation package with a detailed geometry. For the electro-magnetic showers, GEANT4, GEANT3 and EGS are possible codes which may be used. Checking results with more than one code would 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).

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

**FY2004 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 $\beta$-source (Ruthenium) 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.

**FY2005 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**

FY 2003. Computers, travel, graduate student, 1 undergrad.

FY 2004. 0.2 FTE Technician, graduate student, 2 undergrads, travel, 0.25 FTE post-doc, equipment (Ru source, cosmic-ray test stand, scintillators, optical readout, photo-detectors, absorber), machine shop labor.

FY 2005. 0.3 FTE Technician, graduate student, 0.5 FTE post-doc, equipment (KU share in prototype module), machine shop labor, 2 undergrads, travel.

**Three-year budget, in then-year K$**

**Institution:** University of Kansas

---

\(^2\)although it is no substitute for test-beam
<table>
<thead>
<tr>
<th>Item</th>
<th>FY 2003</th>
<th>FY 2004</th>
<th>FY 2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>0</td>
<td>18</td>
<td>33</td>
<td>51</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>4</td>
<td>9</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td><strong>Total Salaries and Wages</strong></td>
<td><strong>19</strong></td>
<td><strong>43</strong></td>
<td><strong>60</strong></td>
<td><strong>122</strong></td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>5</td>
<td>12</td>
<td>17</td>
<td>34</td>
</tr>
<tr>
<td><strong>Total Salaries, Wages and Fringe Benefits</strong></td>
<td><strong>24</strong></td>
<td><strong>55</strong></td>
<td><strong>77</strong></td>
<td><strong>156</strong></td>
</tr>
<tr>
<td>Equipment</td>
<td>5</td>
<td>35</td>
<td>45</td>
<td>85</td>
</tr>
<tr>
<td>Travel</td>
<td>5</td>
<td>6</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>1</td>
<td>10</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total direct costs</strong></td>
<td><strong>35</strong></td>
<td><strong>96</strong></td>
<td><strong>148</strong></td>
<td><strong>289</strong></td>
</tr>
<tr>
<td>Indirect costs</td>
<td>14</td>
<td>28</td>
<td>47</td>
<td>89</td>
</tr>
<tr>
<td><strong>Total direct and indirect costs</strong></td>
<td><strong>49</strong></td>
<td><strong>124</strong></td>
<td><strong>195</strong></td>
<td><strong>368</strong></td>
</tr>
</tbody>
</table>

References

6.11. Optimization of LC detector elements for physics analysis (UCLC)

Calorimetry

Contact person: Mark Oreglia  
email: m-oreglia@uchicago  
phone: (773) 702-7446

Chicago

FY 2003: $15,000  
FY 2004: $102,000  
FY 2005: $152,000
Proposal to the
University Consortium for a Linear Collider

August 21, 2002

Proposal Name
Optimization of LC detector elements for physics analysis.

Classification (accelerator/detector: subsystem)
Detector: calorimeter (+ tracker).

Personnel and Institution(s) requesting funding
Kelby Andersen, Ed Blucher, Frank Merritt, Mark Oreglia, James Pilcher (University of Chicago)

Collaborators
Argonne National Lab, Northern Illinois University

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

Project Overview
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 quantity 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.

In addition to the simulation-based studies, we will develop readout electronics for calorimeter prototypes under study at ANL and NIU. The goal of this electronics development is to beam-test prototypes on a short time scale. For both the simulation work and the electronics design, we anticipate collaborative work with ANL and 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

1
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. Andersen, 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(s).

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.

**FY2003 Project Activities and Deliverables**

In year-1 we will 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.

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.

**FY2004 Project Activities and Deliverables**

During year-2, physics analyses will be refined and comparisons of signals and backgrounds will be made for the range of detector parameters under consideration. At this point we will be able to comment on how calorimeter technologies under consideration compare to the optimization of our study.

In this year we will also develop electronics for calorimeter prototypes and beam tests of ANL and NIU calorimeter prototypes. The Chicago EFI electronics design group has a long history of development of such systems, and has recently designed the hadron calorimeter electronics for ATLAS. We feel that the ATLAS design can be exploited at low overall design cost.

**FY2005 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 only undergraduate research assistants and travel. In the remaining years a graduate student is taken on and also a postdoctoral RA is added (at the 30% level in year-2 and full time in year-3); the travel allowance is increased accordingly. The “Other direct” category is for graduate student tuition.
<table>
<thead>
<tr>
<th>Item</th>
<th>FY 2003</th>
<th>FY 2004</th>
<th>FY 2005</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>0</td>
<td>22</td>
<td>45</td>
<td>67</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>0</td>
<td>21</td>
<td>21</td>
<td>42</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Total Salaries and Wages</td>
<td>6</td>
<td>49</td>
<td>72</td>
<td>127</td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Total Salaries, Wages and Fringe Benefits</td>
<td>7</td>
<td>54</td>
<td>82</td>
<td>143</td>
</tr>
<tr>
<td>Equipment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Travel</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>0</td>
<td>12</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>Total direct costs</td>
<td>10</td>
<td>71</td>
<td>104</td>
<td>185</td>
</tr>
<tr>
<td>Indirect costs</td>
<td>5</td>
<td>31</td>
<td>48</td>
<td>84</td>
</tr>
<tr>
<td>Total direct and indirect costs</td>
<td>15</td>
<td>102</td>
<td>132</td>
<td>269</td>
</tr>
</tbody>
</table>

Calorimetry

Contact person: Yasar Onel
e-mail: yasar-onel@uiowa.edu
phone: (319) 335-1853

Fairfield
Iowa

FY 2003: $0
Project name

Micro-machined Vacuum Photodetectors

Classification (accelerator/detector:subsystem)

Detector:subsystem

Institution(s) and personnel

University of Iowa, Department of Physics and Astronomy:
Yasar Onel (professor) Co-PI, E. Norbeck (professor), J.P.Merlo, A.Mestvirisvili (post-doc), U.Akgun, A.S. Ayan, F. Duru (grad.students), I.Schmidt (Mechanical Engineer), M.Miller (electronics engineer), Jon Olson (undergrad. scholar)

Fairfield University, Department of Physics:
Dave Winn (professor) Co-PI, V.Podrasky (engineer), C.Sanzeni (programmer)

Bogazici University, Department of Physics, Istanbul, Turkey:
Erhan Gülmez (professor)

Cukurova University, Department of Physics, Adana, Turkey:
Gulsen Onengut (professor)

METU, Department of Physics, Ankara, Turkey:
Ramazan Sever (professor)

INFN-Trieste and University of Trieste, Department of Physics, Italy:
Aldo Penzo (professor)

Contact person

Yasar Onel
yasar-onel@uiowa.edu
(319)335-1853

Project Overview

Introduction:

In conjunction with NanoSciences Corporation, Oxford CT and Burle Industries, Lancaster PA, we propose to develop the next generation of high efficiency lightweight, low noise, high rate, large area multi-pixel photomultiplier tubes. Many new experiments rely, in part, on state-of-the-art light detection technology. In this proposal we present a novel approach to developing both silicon micro-machined MCP/dynodes and a high
secondary electron yield diamond based transmission secondary electron (TSE) dynode photomultiplier that could play an important role in producing a detector suitable for use in:

(a) High Magnetic Field Applications, such as in collider detector calorimeters or trackers.

(b) High Rate Photon Counting applications, often in all of the above.

Using proximity focus, the transmission dynode gain mechanism is relatively insensitive to magnetic fields. Additionally, Si-MCP may have channels as small as 1-2 microns, thereby also enhancing high magnetic field performance.

The robust negative electron affinity condition that can be stabilized on diamond film surfaces together with newly discovered methods for highly textured growth of (100) oriented diamond films coupled with a miniaturized silicon micro-machined approach for supporting a transmission dynode stack making possible a low profile light weight imaging photomultiplier with excellent single photoelectron detection.

Coupled with the above, advances in micro-machined silicon or amorphous quartz MCP or dynodes or channelized voltage-standoffs offer a significant performance potential. Micro-channel plates (MCP) have been fabricated from standard silicon wafer substrates using a novel silicon micromachining process, together with standard silicon photolithographic process steps. The resulting Si-MCP micro-channels have dimensions of ~0.5 µm up to ~25 µm, with aspect ratios up to 300, and have the dimensional precision and absence of interstitial defects characteristic of photolithographic processing, compatible with positional matching to silicon electronics readouts. The open channel areal fraction and detection efficiency may exceed 90% on plates up to 300 mm (12”) in diameter. The resulting silicon substrates can be converted entirely to amorphous quartz (qMCP). The strip resistance and secondary emission are developed by controlled depositions of thin films, at temperatures up to 1,200°C, also compatible with high-temperature brazing, and can be essentially hydrogen, water and radionuclide-free. Novel secondary emitters and cesiated photocathodes can be high-temperature deposited or nucleated in the channels or the first strike surface. Summary of Si-MCP features:

- Pore Sizes/Resolution: Between ~0.5 µm - ~25 µm
- Pore Size Uniformity: <±0.5% in x and y.
- Pore Placement/Position Uniformity: <±0.5 µm in x-y over 25 mm plate.
- Absent/Missing/Displaced Pores: None
- Aspect Ratios: may exceed 300:1
- Open Pore Areal Fraction/Detection Efficiency: >95% with tapered channel input.
- Plate Sizes: to 90 mm diameter now, extendable to ~300 mm (12” wafer substrates).
- Chevron: up to 45° tilt demonstrated.
- Bake-out temperatures: <1,200°C Si-MCP, <1,400° Q-MCP
- Plate Resistance/Current: Adjustable from 1 KΩ - 10 MΩ/cm².
• Activation Processes: CVD, electroplating, gas, liquid &; phase reactants, (others).
• Gain: >1,000 at 1KV, comparable to lead-glass MCP
• SE Materials: silicon oxides, metal oxides & silicides, diamond, GaP, (others).
• Compatible with direct-front-surface deposited cesiated photocathodes.
• Compatible with high temperature deposition of high SE first strike materials.
• Compatible with high temperature metal/ceramic brazing.
• Low or negligible hydrogen or water content.
• Low or negligible self-radioactivity possible.
• High radiation resistance
• Fully compatible with silicon lithographically patterned readout, silicon processing.
• Fully or partially oxidizable to amorphous quartz.
• Optically opaque channel walls if not fully oxidized.

Background

Forecasts for the near future include a fusion of photomultiplier and imaging technology, which combine the response time of photomultipliers with the high quantum efficiency and multi pixel (imaging) capability of CCD-like devices. It is envisioned that future developments will include the realization of multi-pixel devices capable of fast readout, similar to a photomultiplier, and with photocathodes having high quantum efficiency and broadband spectral response. The realization of such a dynode, based upon diamond, and diamond like carbon layers, will lead to a new class of simple, efficient, low-noise multi-pixel photomultipliers (PMT’s) as well as improved imaging devices with lower noise factors, for military, scientific and commercial applications. Our premise is to start with a detection mechanism that has inherent high gain with excellent signal to noise performance and incorporate that mechanism into a micro-machined, monolithic structure that is readily interfaced to high speed digital signal processing and memory circuits using surface mount technology. The advantages of this approach are: (1) high gain can be achieved in a compact structure, (2) superior noise and imaging characteristics, (3) elimination of the many hand assembly steps in conventional PMT manufacturing through parts consolidation, (4) complete compatibility with Si fabrication processes, (5) ability to integrate with high speed read out, digital signal processing (smart pixels) and nonvolatile data storage circuitry, (6) low power consumption when coupled with a compact Cockcroft-Walton or Greinacher-type voltage multipliers for individually powered dynodes avoiding a resistor biasing chain, (7) extremely low transit times due to the small dynode depth and (8) the low angle electron trajectories, resulting in low transit time jitter and fast rise times.

In order to demonstrate the device can be built, several major technical hurdles must be surmounted. First substantial TSE gain from a diamond structure must be demonstrated, second, the noise properties of the TSE in a proximity focused imaging device need to be investigated and third, fabrication of the micro-machined dynode structure, photocathode deposition and transfer and vacuum enclosure needs to be developed. This proposal deals with the first and second hurdles and employs a proximity focused MCP based intensifier as a means of studying the diamond TSE even though a multi diamond TES miniature
Yasar Onel, University of Iowa; Dave Winn, Fairfield Univ. 9/3/2002

PMT is the desired final structure. The MCP based intensifier is a convenient and relevant laboratory for investigating the diamond TSE performance.

The technical objectives of this proposal are (1) to explore the use of highly (100) textured diamond films as high yield TSE dynodes for use in compact high efficiency photomultipliers, (2) to develop and verify the TSE gain, noise and MTF of diamond films in an intensifier arrangement, (3) verify gain rate and lifetime characteristics of Si-MCP.

Proposed Research and Development:

- Growth of textured diamond films
- Measurement of TSE yield
- Diamond TSE-Si-MCP tube fabrication
- Tube Tests
- Final Report

Growth of textured diamond films

This task develops the deposition of highly (100) textured diamond films on Si using an Astex plasma diamond growth reactor. Films will be grown on (100) Si substrates which will be subsequently processed to open up windows on the Si revealing the diamond film. The window structures will be prepared using lithography and silicon anisotropic etching. During the final stages of diamond film growth boron will be introduced into the diamond reactor to make the final diamond surface conducting. This surface will be on the input side for the electron beam. The B doped surface will have a positive affinity while the diamond surface revealed by removal of the Si will be processed to an NEA condition before the TSE yield measurement. This task is given 4 months to complete from mask ordering to part production.

Measurement of TSE yield

This phase involves many measurements of the transmission secondary electron yield of the thin film dynodes fabricated above. The TSE yield will be measured using a secondary electron measurement that Fairfield and NanoSciences has constructed for measuring reflection secondary electron yields. The TSE yield measurement will be carried out as a function of incident electron energy with and without a bias voltage applied across the diamond film. The electron affinity of the diamond surface will be measured using UPS, ultraviolet photoelectron spectroscopy in a VG Microlab 310 surface analysis machine. The TSE yield will be correlated to the degree of preferred orientation in the film to try and verify our assertion that highly textured films will show higher TSE yield.
Tube Construction

The Diamond TSE dynode structures measured above will be sent to Burle when they will be fabricated into intensifier tubes, using a Si-MCP so that sufficient gain for measurements can be obtained. Fairfield will obtain Si-MCP from NanoScience with rims and electrodes matched to the requirements from the diamond TSE dynode provided to Burle. The intensifiers will be similar to that shown in partial cross-section in Figure 4, using proximity focusing between photocathode and the diamond TSE and between the diamond TSE and the MCP input face. The photocathode will be a standard type either bi-alkali or better in the visible, depending on immediate availability.

Tube Tests

The tubes will be shipped to Iowa for TSE gain, Si-MCP gain, linearity, rate, and spatial resolution tests. Tests in magnetic fields up to 2T will be performed. A very important test will be lifetime tests of both the Si-MCP and the diamond TSE dynodes. These tests will last at least 2 months.

Note: there is no budget request in this proposal at this time. We may apply for funding in the future.
6.13. Cherenkov compensated calorimetry (LCRD)

Calorimetry

Contact person: Yasar Onel
email: yasar-onel@uiowa.edu
phone: (319) 335-1853

Fairfield
Iowa
Iowa State

FY 2003: $40,160
Project name
Cherenkov compensated calorimetry

Classification (accelerator/detector:subsystem)
Detector:subsystem

Institution(s) and personnel
University of Iowa, Department of Physics and Astronomy:
Yasar Onel (professor) Co-PI, E. Norbeck (professor), J.P.Merlo, A.Mestvirisvili (post-doc ), U.Akgun, A.S. Ayan, F. Duru (grad.students), I.Schmidt (Mechanical Engineer), M.Miller (electronics engineer), Jon Olson (undergrad. scholar)

Fairfield University, Department of Physics:
Dave Winn (professor) Co-PI, V.Podrasky (engineer), C.Sanzeni (programmer)

Iowa State University, Department of Physics:
Walter Anderson (professor)

Bogazici University, Department of Physics, Istanbul, Turkey:
Erhan Gülmez (professor)

Cukurova University, Department of Physics, Adana, Turkey:
Gulsen Onengut (professor)

METU, Department of Physics, Ankara, Turkey:
Ramazan Sever (professor)

INFN-Trieste and University of Trieste, Department of Physics, Italy:
Aldo Penzo (professor)

Contact person
Yasar Onel
yasar-onel@uiowa.edu
(319)335-1853

Project Overview
Introduction:

We propose to study a novel idea to employ a dual readout calorimeter, simultaneously measuring the Cerenkov light with ionization on hadron-initiated showers on an event-by-event basis to compensate calorimeters, and to achieve precision energy resolution.

Briefly, the idea is that as a shower fluctuates more into charged pions rather than neutral pions, that a Cerenkov signal generated in a transparent absorber/active medium, which arises mainly from the e-m component of the shower, is reduced in a correlated fashion with the ionization signal, thereby enabling a correction of the energy given by an ionization signal.
Preliminary infinite media GEANT simulations have indicated that the correction can in principle enable an energy resolution substantially better than existing calorimeters [1], which rely instead on suppressing the e-m signal relative to the hadronic signal.

Technical Proposal:

If a hadron shower were to fluctuate entirely into neutral pions (i.e. an extreme charge exchange for example), ionization and Cerenkov signals both can achieve excellent resolutions if sufficiently well sampled (NaI and Pb-glass calorimeters can have excellent resolutions on electrons, for example). However, as the hadron shower fluctuates into charged pions and neutrons (etc.), both signals or measures of the energy, the ionization and Cerenkov signals, become degraded. In general, with a single calorimeter signal, it is not possible to know how much the signal is degraded or reduced compared with the initial hadron energy. However, in preliminary studies, the Cerenkov signal appears to degrade at a much larger rate as a function of $F_{pi}$, the fraction of charged pions, compared to ionization signals (both scintillation light from LScint, BaF2, and NaI, and a drifted ionization signal collected from LArgon were studied). If the Cerenkov and the ionization signals are highly correlated, then measuring both will determine how large the fluctuation is on any event, which can be then used to correct the energy.

These preliminary homogeneous calorimeter GEANT studies done some years ago indicate that an achievable energy resolution may allow a stochastic term less than $20%/\sqrt{E}$, perhaps as low as $15%/\sqrt{E}$, with a constant term tuned less than 1% on a hadron calorimeter. We propose to make an extensive MC study of designs which could be more easily be used in practice.

Historically, the E1A neutrino calorimeter, a pure liquid scintillator ionization hadron calorimeter, achieved a stochastic term of $11%/\sqrt{E}$ (GeV), showing the remarkable effect of large (i.e. $1/\sqrt{N}$) signals, but with a constant term of 9% [8]. On the other hand, the SPACAL lead-fiber calorimeter achieved a hadron energy resolution of ~$35%/\sqrt{E}$, with a constant term of about 1%, as limited by the packing fraction of 20%. A compensated Cu-SciFi calorimeter constructed for SSC and the scintillator tile-Cu absorber calorimeters for ATLAS achieve resolution terms of about 60%-50%/√E, largely due to the low compensated packing fraction of about 2-3%. If the packing fractions in these practical devices were to be increased to about 25%-30%, the stochastic term could be reduced by ~x3, provided that the sampling fraction $F$ and the sampling thickness $d$ are such that the sampling fluctuations are less than the sampled energy statistics [5] [i.e. $s/E = (d/F)^{0.5} \times (E)^{-0.5}$, where $d$ is the sampling thickness and $F$ is the sampling fraction.] However, the constant term would increase to about 7%-8%. Thus it is worth considering if a "2nd" measurement could be used to adjust the constant term downwards, while allowing a large signal for a small stochastic term. Using typical SPACAL data for $F_{pi}$ [6], [7] the pion fluctuation fraction, and estimating the contribution from nuclear breakup by Wigmans [7], measuring the energy of the e-m component to about +/-30%/√E should allow the adjustment of the constant term to ~1%.

The very first absorption calorimeters used homogeneous media Cerenkov light, in order to measure electromagnetic shower energy. Modern Pb-glass and especially water (Super-K) calorimeters achieve excellent resolutions on electrons (<2%/√E 9,000
p.e./GeV). However, on hadrons, both Pb-glass walls [2] and swimming pool calorimeters [3] have achieved a hadronic energy resolution of ~35%/√E, but with a constant term of ~10%.

Recent results by the CMS Forward Calorimeter Group (in which the proposers are participants) have shown that sampling Cerenkov calorimeters consisting of quartz fibers embedded in Cu serve as an adequate forward calorimeter[4]; the results indicate that the signal response is approximately given by: (1 p.e./F)(NA/0.2)\(^{1.5}\), where F is the fiber packing fraction in percent, and NA is the fiber numerical aperture. At F~1%, at NA=0.2 and 0.4 mm diameter fibers, the Cu-fiber calorimeter achieves an energy resolution of about 100%/√E(GeV) on electrons, with a constant term <0.1%. With a F~25% packing fraction of NA~0.6 200 micron core clear fibers (n~1.6), one would therefore expect an electromagnetic energy resolution of better than ~10%/√E. This would be sufficient to measure Fpi, the fluctuations in the shower, to about +/- 30%/√E, which would in principle allow a constant term of 1-2%. Using similar scaling for a packing/sampling fraction of the ionization medium embedded in Cu, at say, F~25% for the ionization medium and d~0.5 mm thick sampling, one might obtain s/E ~15%-18% (as scaled from either the ATLAS (calorimeter), with a constant term near 1%.

If successful in R&D, the main uses in LC calorimeters would be to:

(1) High Resolution E-M Calorimeter Compensation for Jet Energy Resolution

To correct for jet energy from hadrons interacting in high resolution e-m calorimeters, at present, the use of an extremely non-compensated but very high resolution e-m calorimeter in front of a compensated hadron calorimeter results in relatively poor jet energy resolution, as in the CMS calorimeter system, where a PbWO\(_3\) front end with superb em resolution results in a jet resolution degraded to ~100%-120%/√E, mainly from jet energy deposited in an uncompensated, e/h~2, ~1-2Lint em calorimeter. For example, in a lead tungstate or cerium fluoride calorimeter in the front of LC experiments, 2 photo-readouts would be provided, with optical filters which accept either the scintillation light or the Cerenkov light generated in the crystal. Or with a Si or LArgon e-m calorimeter, additional Cerenkov sampling via fibers or plates would be provided.

(2) Intrinsic Hadron Calorimeter Energy Resolution

Increase hadronic and jet energy calorimeter energy resolution sufficiently so that Z\(_0\) identification and other precision dM/M and missing transverse energy measurements by jets becomes more feasible i.e., so that at least the intrinsic particle energy resolution is such that the calorimeter contribution to the jet-jet mass width is below the intrinsic Z or narrow Higgs widths this may require s/E ~ 25%/√E (together of course with requirements on increased transverse segmentation and adaptive global jet-cone algorithms which are not part of this study).

(3) Background Rejection
The Cerenkov signal in CMS prototype copper-quartz-fiber forward calorimeter for 375 GeV single pions has been shown to rise in <1 ns and to fully develop in less than 5 ns (0% → 95% of the signal on the end of a cable). The superb timing available has been shown in MC to allow beam-gas and beam-halo muon rejection, and to associate signals with the beam crossing and with other calorimeter cells to a high enough precision to play a useful role in determining interesting events from the multiple events in an LHC crossing (very different from LC of course). However, the rate capability (small PMT have been run near 1 GHz for LHC tests) and timing of a well-designed Cerenkov fiber or plate component may play a crucial role in the environment of the LC interaction region where a calorimeter may still receive a considerable load of uninteresting signals & potential pile-up from beam-associated backgrounds and high instantaneous rates (albeit for short times, say ~10s of ns per crossing). Multiple measurements of the same hadron/calorimeter shower allow consistency checks for event-associated upsets (for example a splash through a PMT or a FET). Therefore a simultaneous Cerenkov-signal readout of an ionization calorimeter may be interesting on these grounds alone.

Proposal
We therefore propose for FY 03:

Cerenkov Compensation MC Studies:
Study Cerenkov Compensation schemes using GEANT and LC simulation tools:

(a) MC "Calibration": Tune existing codes and reproduce the reported resolutions and response of existing calorimeters: the ATLAS scintillator plate-WLS fiber calorimeter, the CMS Forward Cerenkov Fiber calorimeter, and of at least one tested/published drifted-ion sampling calorimeter (Si or LArgon), and of at least on homogeneous crystal calorimeter. These will include full propagation of individual signal photons or electrons (for example, as captured on the WLS fibers, and realistic photodetectors, including both APDs and PMTs).

(b) WLS Fiber-Scintillator + Clear Fiber Geometry: MC Study an ATLAS-style/Gildmeister [6] Scintillating Tile/fiber Cu absorber Calorimeter geometry with high scintillator packing fractions, up to 40% of scintillator, and up to 40% of clear Cerenkov radiator fibers. (A very brief study will also be made using WLS fibers on clear C-radiators, but this is anticipated to fail.)

(c) Plate Geometry: MC Study of a classic plate absorber geometry: Cu absorber plate + [scintillator, LArgon, or Silicon] plate + Cerenkov plate. The Cerenkov plate would be read-out using an APD array

(d) All Fiber Geometry: MC study of Cu-absorber + Scintillating Fiber + Clear Fiber Calorimeter.

(e) Homogeneous Calorimeter Geometry: MC study of the simultaneous Cerenkov readout of e-m crystal calorimeter (lead tungstate), using filters and 2 photodetectors, and of collecting drifted ions and Cerenkov light in LXe. The authors have shown in detail that Cerenkov light and ionization light can be measured independently and simultaneously in LScintillator using filters (somewhat counterintuitively, the Cerenkov
light is measured by using a low-pass filter i.e., the long-wavelength Cerenkov light despite the lower yield because of the shifting properties of the fluorine in the scintillator).

**Relevant Experience**

Y. Onel and D. Winn have jointly proposed the quartz fiber calorimetry for the CMS forward Calorimeter (HF) in January 1994 after prototyping the quartz fiber calorimetry using SSC GEM closeout finds. There are now 6 U.S. and 9 international institutions (15 in total) in the CMS-HF group.

The U.S. CMS HF group at Iowa was responsible for:

1- HF detector prototypes
   a. Engineering design of prototypes and preproduction prototypes and manufacturing the modules and components (in the machine shop at University of Iowa.)
   b. Engineering design and manufacturing of the Readout box for the preproduction modules (in the machine shop at University of Iowa.)
   c. Engineering design and manufacturing of the optical system for the preproduction modules.
   d. Engineering design of the HF calibration system (LASER and LED) and development of source calibration systems for the preproduction modules.
   e. Production and engineering design of the HCAL LED drivers (HB, HE, HO and HF) and manufacture of prototypes in the electronic shop at the University of Iowa.

2- Selection and purchase of US quartz fibers in addition to the responsibilities of procurement procedures, contracts, insurance, quality control at manufacturer (CMS IN 2002/028) and delivery schedules and final delivery.

3- Fiber radiation damage tests and studies at Iowa LIL/CERN facilities

4- Selection and purchase of Photomultiplier Tubes (PMT’s) in addition to the responsibilities of procurement procedures, contracts, insurance, delivery schedules and final delivery.

5- Construction of the CMS-HF IOWA PMT test station facility.

6- Test and quality control of the HF PMT’s and maintenance of a web-based database.

7- Design and construction of the HF light guides for the first two wedges (2 of 36) in the University of Iowa machine shop. Procurement of the light guide material for the remaining 34 wedges.

8- Design and construction of the source distribution mechanics, including source tubing couplers and coupler pins in the (University of Iowa machine shop.)

**Deliverables**

Because of the limited funding, we will concentrate on the Monte Carlo simulations in FY03. We will produce a Report/Research Document showing the results and the details of our Monte Carlo simulations for the specific geometries and configurations as shown in our proposal to design a Cherenkov Compesated Calorimeter for LC. We will initially focus on the simulations/study necessary for developing the detector requirements and estimating systematic errors. If we are successful in 03, we propose to continue with our R&D by constructing a prototype in 04.
### Budget-FY03

<table>
<thead>
<tr>
<th>Institution</th>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>Partial support of one grad. student</td>
<td>$2.4k</td>
</tr>
<tr>
<td>Iowa</td>
<td>Partial support of one post-doc</td>
<td>$16k</td>
</tr>
<tr>
<td>Fairfield</td>
<td>Partial support for undergrad. students</td>
<td>$4.8k</td>
</tr>
<tr>
<td>Iowa</td>
<td>Travel</td>
<td>$2.4k</td>
</tr>
<tr>
<td>Fairfield</td>
<td>Travel</td>
<td>$3.2k</td>
</tr>
<tr>
<td>IowaState</td>
<td>Travel</td>
<td>$3.2k</td>
</tr>
<tr>
<td></td>
<td>Indirect cost @ 25.5%</td>
<td>$8.16k</td>
</tr>
<tr>
<td></td>
<td>Grand total</td>
<td>$40.16</td>
</tr>
</tbody>
</table>

**REFERENCES:**


[8] ATLAS Tile Calorimeter TDR CERN/LHCC/96-42


[10] A.Benvenuti et al., NIM 125 447 (1975)
6.14. Study of Resistive Plate Chambers as Active Medium for the HCAL (LCRD)

Calorimetry

Contact person: José Repond
email: respond@hep.anl.gov
phone: (630) 252-7554

Argonne
Boston University
Chicago
Illinois

FY 2003: $50,100
Project name

Study of Resistive Plate Chambers as Active Medium for the HCAL

Classification (accelerator/detector:subsystem)

Detector

Institution(s) and personnel

Argonne National Laboratory: Gary Drake (electronics engineer), José Repond (staff scientist), Rik Yoshida (staff scientist)

Boston University: John Butler (professor), Meenakshi Narain (professor)

University of Chicago: Mark Oreglia (professor) et al., see proposal submitted to NSF

University of Illinois at Champaign – Urbana: Jon Thaler (professor)

Contact person

José Repond
repond@hep.anl.gov
(630)-252-7554

Project Overview

The optimal application of Energy Flow Algorithms for the measurement of hadronic jets requires a finely segmented electro-magnetic and hadronic calorimeter (HCAL). The latter is envisaged to be a sandwich type calorimeter and to contain cells of the order of 1 cm², read out separately for each layer. The resulting number of readout channels is approximately 5x10⁷. Detector simulation studies have demonstrated that, given the fine segmentation, the energy resolution is preserved with only a digital readout of the HCAL.

Our aim is to develop an active medium for the HCAL, which is reliable, simple to build, comparatively thin (under 10 mm), with the ability to be segmented laterally into cells of 1 cm², and affordable. Resistive Plate Chambers (RPCs) have been utilized in a number of HEP experiments over the past decade and appear to satisfy all of the above requirements. We propose to study the suitability of RPCs as active medium for the HCAL.

Description of Resistive Plate Chambers

A sketch of a generic Resistive Plate Chamber is shown in Figure 1. Two parallel plates of high resistivity, ρ = 10¹⁰ to 10¹² Ωcm generate a uniform, intense electric field, about
4kV/mm, in a typically 2 mm wide gas gap. The plates are coated, on the external sides, with thin graphite layers connected to high voltage and ground, respectively. Due to their high surface resistivity of about 100 kΩ, these graphite electrodes are transparent to the transients of electrical discharges generated in the gas. Capacitive signal readout is therefore possible through pads which are insulated from the graphite carrying the high voltage by a layer of mylar.

![Sketch of a generic Resistive Plate Chamber.](image)

The simplicity of the concept of these chambers allows for a large variety of design choices. Two types of resistive plates have been used for the construction of most chambers: glass and bakelite. The advantage of bakelite is its somewhat faster recharging capability; however the optimal performance requires the application of a coat of linseed oil to the inner surface of the plates - a somewhat delicate operation. Chambers have been built with one single gap, some as wide as 8 mm, or multiple and smaller gaps for better timing resolution at uncompromised signal efficiency. The thickness of the glass plates, typically 2 mm, can be varied; however thinner plates will be distorted by the forces resulting from the high electric field between the plates. The resistivity of the graphite layer can be varied and will affect both the rate performance and the amount of cross-talk between adjacent readout pads. Finally, the chambers can be operated either in the avalanche mode (at a lower high voltage setting) or in streamer mode. The collected charge in the streamer mode is approximately a factor of 50 larger than in the avalanche mode. Different gas mixtures have been explored, some with the ability of efficiently suppressing streamers.

In general, the physics of RPCs is well understood and Monte Carlo programs exist which simulate the various physics processes occurring when the chambers are traversed by a particle. More details on the current status of research related to RPCs and of recent applications of RPCs in HEP can be found in the contributions to last years workshop dedicated to these chambers [1].
Rate considerations

RPCs are slow to recharge: typically recharging times of 1 (streamer mode) and 0.1 ms (avalanche mode) have been observed. The times depend on several factors, such as the resistivity of the graphite layer, the material and the resistivity of the plates and the applied high voltage.

Assuming a linear collider operating at $\sqrt{s} = 500$ GeV with a luminosity of $0.5 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$, the rate of annihilation events is approximately 1 event every 50 s and, therefore, the recharging rate of the chambers is not a concern. More worrisome is the rate of $2\gamma$ events leading to pairs of muons or to hadrons traversing or entering the hadron calorimeter.

The total cross section for $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ ($e^+e^- \rightarrow e^+e^-h$) is estimated [2] to be 420 nb (162 nb), leading to a rate of $2.1 \cdot 10^3$ muon pairs (810 hadron events) per second. These rates are comparable to the recharging rate of the chambers when operated in streamer mode and, given the fine segmentation of the hadron calorimeter, should not pose a problem.

The calculation for the process $e^+e^- \rightarrow e^+e^-h$ has also been verified using the PYTHIA Monte Carlo Program. The resulting cross section is somewhat smaller, 34 nb, leading to a rate of 171 events per second [3]. Figure 2 shows the rate of particles/100 s as a function of the polar angle at the production vertex.

![Figure 2: Rate of particles per 100 seconds from the process $e^+e^- \rightarrow e^+e^-h$ as a function of the polar angle, as predicted by PYTHIA.](#)

Assuming the geometry of the TESLA detector as publicized in the TESLA Technical Design Report, these events generate a negligible rate of particles in the barrel hadron calorimeter. However, each endcap calorimeter sees a rate of approximately 613 particles
(mostly pions) per second with an average energy of 1.5 GeV. A cut at 1 GeV, as an estimate of the amount of energy required to traverse the electromagnetic calorimeter located in front of the hadron calorimeter, reduces the rate to 283 Hz. Again, given the fine segmentation of the calorimeter, this rate should not be a problem for the RPCs.

The rates for all $2\gamma$ processes increase logarithmically with energy. For instance, the cross section for $e^+e^- \rightarrow e^+e^-\gamma$ increases from 162 nb at $\sqrt{s} = 500$ GeV to 189 nb at $\sqrt{s} = 800$ GeV.

**Description of project activities**

We will initiate a detailed R&D program to evaluate the merits of RPCs as active medium of the HCAL:

1) We will complete the evaluation of a small number of RPCs which we obtained from other experiments.

2) We will construct a small number of test chambers with various
   - glass and gas gap thicknesses
   - resistivity of the layers of ink (distributing the high voltage onto the glass)
   - geometries of the readout pads.

3) We will develop a readout system based on a one-level discriminator. This system will be used to evaluate the different chamber designs and pad geometries.

4) We will test these chambers in a cosmic ray test stand and evaluate their:
   - noise characteristics
   - signal strength versus applied high voltage and for different gas mixtures
   - efficiency for the detection of minimum ionizing particles
   - cross talk between adjacent channels
   - long term stability

5) Following the completion of the above tests, we will design and build a small test section of an (electro-magnetic) calorimeter, approximately 25 cm in all three dimensions. This test section will feature the order of 10,000 readout channels. The electronic readout system will be based on a custom chip. The mechanical set-up will be designed such as to allow for easy implementation of other active media, as they might become available.

6) We will test this calorimeter in particle beams which are available at the major particle physics laboratories, such as DESY and CERN or elsewhere. These tests will be important in verifying the functionality of the chambers and their electronic readout system.

7) We will initiate long-term tests of our prototype chambers to assess their stability over long periods of time and to detect any possible aging effects.

8) Contingent on the successful tests of our small (electro-magnetic) calorimeter, we will design and build a test section of the hadronic calorimeter, sized approximately 1 m$^3$, which is sufficient to contain hadronic showers both laterally and longitudinally. This calorimeter section will again be subjected to extensive tests in particle beams.
We expect to complete items 1) – 4) in FY 2003, items 5) – 6) in FY 2004, initiate item 7) in FY 2004 and item 8) in FY 2005.

**Engineering and technical effort during FY2003**
The following engineering and technical activities are planned for FY2003:

1) Construction of a small number of test chambers with different dimensions (glass and gas gap thicknesses.) This involves the cutting and gluing of glass.
2) Development of a technique to apply layers of resistive ink (graphite) with different, but uniform thicknesses, leading to specific values of the surface resistivity.
3) Design and production of spacers and rims (out of plastic) for the construction of the chambers needed for the assembly of the electro-magnetic size calorimeter.
4) Design and building of a readout system for the test chambers and possibly for the electro-magnetic size calorimeter. The readout scheme will include only the digital information. The large number of channels of both the electromagnetic size calorimeter and the test section of the HCAL prevents the deployment of an analog readout.

**Budget requests**

<table>
<thead>
<tr>
<th>Institution</th>
<th>Item</th>
<th>FY 2003</th>
<th>FY 2004</th>
<th>FY 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne</td>
<td>Summer students, other professionals</td>
<td>$0</td>
<td>$55,000</td>
<td>$55,000</td>
</tr>
<tr>
<td>Argonne</td>
<td>Materials to build chambers / readout</td>
<td>$0</td>
<td>$10,000</td>
<td>$40,000</td>
</tr>
<tr>
<td>Boston</td>
<td>Students, other professionals</td>
<td>$29,100</td>
<td>$30,000</td>
<td>$30,000</td>
</tr>
<tr>
<td>Boston</td>
<td>Engineer</td>
<td>$10,000</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Boston</td>
<td>Materials to build chambers / readout</td>
<td>$5,000</td>
<td>$32,500</td>
<td>$62,500</td>
</tr>
<tr>
<td>Illinois</td>
<td>Students</td>
<td>$3,000</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Illinois</td>
<td>Engineer / Technician</td>
<td>$0</td>
<td>$10,000</td>
<td>$30,000</td>
</tr>
<tr>
<td>All</td>
<td>Travel</td>
<td>$3,000</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$50,100</td>
<td>$160,500</td>
<td>$240,500</td>
</tr>
</tbody>
</table>

**References**


The total cross sections obtained with PYTHIA and analytically through the formulas given in [2] differ by a factor of ~5. The reasons for this discrepancy are being studied. The conclusions do not change significantly with either total cross section.