6. Calorimetry
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. Dijet mass must be measured to a precision of \(~3\) GeV or, in terms of jet energy resolution, \(\sigma(E) \approx 0.3\sqrt{E} \) (\(E\) in GeV). [52]

The most important aspect of the calorimeter is to provide accurate measurements of the four-momenta of charged and neutral particles, individually and in jets. In the present parlance of calorimetry, this is best achieved by an Energy Flow algorithm in three dimensions. [53] The Energy Flow (or Particle Flow) Algorithm consists of following the tracks measured by the tracking detector into the calorimeter and measuring their respective energy deposits. These particles, which typically carry \(~60\)% of a jet’s total energy, are measured with much higher precision by the magnetized inner tracker. The electromagnetic calorimeter (ECal) is used to measure EM showers, carrying on average \(~25\)% of jet energy, with a resolution of \(\sigma(E) \approx 0.12\sqrt{E}\). This way, even though the energy resolution of the hadron calorimeter (HCal) for single hadrons may be no better than \(\sigma(E) \approx 0.6\sqrt{E}\), a net jet energy resolution of \(\sigma(E) \approx 0.3\sqrt{E}\) is achievable by using the HCal to measure only the neutral hadrons, typically carrying merely \(~11\)% of the total jet energy.

If realized, a detector for the LC will likely be the first with a calorimeter designed specifically for Energy Flow Algorithms. [54] It will be a challenge to develop algorithms under the unique conditions and constraints of the new facility. These will in turn drive the technology and design choices not only for the calorimeter, but for the inner tracker and the muon systems as well. For the calorimeter to be able to track and isolate charged particles in a jet while staying within a realistic budget, some features favored by traditional algorithms of sampling calorimetry may have to be sacrificed to gain 3-D tracking or imaging capabilities in the calorimeter. Particularly for the hadronic calorimeter, collecting a large number of hits with good position resolution will be more important than estimating the amount of energy associated with each hit. The current favorite designs for the NLC and TESLA calorimeters have \(~30\) layers of \(~0.25\) cm\(^2\) cells totaling \(~25\) radiation lengths in the ECal and \(~40\) layers of 1-10 cm\(^2\) cells totaling \(~4.8\) interaction lengths in the Hcal. [55, 56]

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.

The considerations of cost and the technological challenge in satisfying the desire of having the entire calorimeter immersed in a 4-5 T magnetic field limit the radius of the
calorimeter in the more popular designs. While a finely segmented calorimeter will aid muon measurements, the muon system may be required to serve as a “tail-catcher” for parts of jets leaking through the relatively thin calorimeter.

Several competing technologies have been proposed and are being investigated under a worldwide collaborative effort. [57] Possible alternatives for the ECal include Si-W, Scintillator-W or Scintillator-Pb, and lead tungstate crystals. Plastic scintillators, Resistive Plate Chambers (RPC), and Gas Electron Multipliers (GEM) are all candidates for possible active media for the HCal. Hybrids employing multiple technologies are also possible for both the ECal and the HCal. UCLC and LCRD proposals aim to study these options, with all groups working in close collaboration.

Hardware development must proceed in tandem, and in close cooperation with simulation studies. The design optimization must begin with simulation, while data from test-beam studies of the prototypes will help fine-tune the parameters of the simulation. Development of algorithms and extensive studies of a multitude of physics scenarios are key to designing the detector and charting the physics program. While every group interested in a specific detector technology accepts the responsibility of testing it in simulation, the overall plan involves much more. A flexible yet powerful software environment is required to generate millions of Monte Carlo (MC) events under various scenarios both within and beyond the Standard Model, simulate detector response to those under different options, reconstruct the signatures, tune algorithms, and parametrize detector response for very large volumes of MC events for which full detector simulation is not feasible. Several university groups, including some primarily involved in calorimetry, plan to contribute to the common infrastructure, support, and MC production service for the entire LC community. Increasingly, this effort is converging toward a global unification. Technical and fiscal considerations favor international collaboration in the planning and execution of beam tests as well. [58]

References


### Contents

#### 6. Calorimetry

Overview and contents.................................................................................................................................666

6.1 Design and Prototyping of a Scintillator-based Hadron Calorimeter (Vishnu Zutshi: renewal) .................................................................................................................................671

6.2 Study of the Performance of a Scintillator Based Electromagnetic/Hadronic Calorimeter and Study of the BeamCal (Uriel Nauenberg: renewal) ........................................683

6.4 Particle Flow Studies with the Silicon Detector (SiD) at the International Linear Collider (ILC) (Usha Mallik: renewal) ..................................................................................................................689

6.5 Development of a silicon-tungsten test module for an electromagnetic calorimeter (Raymond Frey: renewal) .................................................................705

6.6 Digital Hadron Calorimetry for the Linear Collider using GEM based Technology (Andy White: renewal) .................................................................................................719

6.9 Development of Particle-Flow Algorithms and Simulation Software for the ILC Detector(s) (Dhiman Chakraborty: renewal) ........................................................................735

6.10 Investigation of ECAL Concepts Designed for Particle Flow (Graham Wilson: renewal) .................................................................................................................................751

6.14 Construction of a Prototype Hadronic Calorimeter with Digital Readout (José Repond: renewal) .............................................................................................................................765

6.16 Dual-Readout Calorimetry for the ILC (Richard Wigmans: renewal) ..................................................787

6.18 Development of a New Concept Detector [also includes vertex, tracking and muon systems] (John Hauptman: new proposal) .............................................................................................................792

6.19 Calorimeter and Muon ID (A.J.S. Smith: new proposal) ........................................................................797

6.20 A Calorimeter based on Scintillator and Cherenkov Radiator Plates Readout by SiPMs (Tianchi Zhao: new proposal) ..................................................................................810
6.1: Design and Prototyping of a Scintillator-based Hadron Calorimeter (renewal)

Calorimetry

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Colorado
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Fermilab
ITEP
Northern Illinois
Pavia

Funds awarded (DOE)
FY04 award: 50,000
FY05 award: 31,500

New funds requested
FY06 request: 50,500
FY07 request: 110,000
Status Report to DOE/NSF for ILC Detector R&D

December 22, 2005

Project Name
Design and Prototyping of a Scintillator-based Hadron Calorimeter.

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

Personnel and Institution(s) requesting funding
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Project Overview
The Northern Illinois University(NIU)/Northern Illinois Center for Accelerator and Detector Development (NICADD) [1] group is interested in calorimeter R&D for the proposed Linear Collider. We are engaged in developing, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet energy measurement using particle-flow algorithms (PFAs). Software simulations/algorithmd 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 hadron calorimeter options suited for, but not limited to, an $e^+e^-$ linear collider.

It is clear that for the Linear Collider to fulfill its physics charter multi-jet final states will have to be exceptionally well measured. In particular, superior resolutions in jet ($30\%/\sqrt{E}$ or better) and missing energy measurements will be critical for discovery and characterization of the new physics as well as for precision tests of the Standard Model (SM). The most promising means to achieving such unprecedented resolutions at the next linear collider is through particle-flow algorithms [2] which require fine lateral and longitudinal segmentation of the calorimeter to individually reconstruct the showers constituting a jet. This approach allows one to make optimal use of the information available in the event: tracker momenta for charged particles and calorimetric energy measurements for photons and neutral hadrons.

The NIU team has been investigating a finely-segmented scintillator-based hadron calorimeter for some time now. This option capitalizes on the marriage of proven detection techniques with novel photodetector devices. Absence of fluids/gases and strong electric fields inside the detector aids longevity and operational stability. The main challenge for a scintillator-based hadron calorimeter is the architecture and cost of converting light, from a large number of channels, to electrical signal. Our studies demonstrate that small cells (6-10 cm$^2$) with embedded Silicon Photomultipliers (SiPMs)/Metal Resistive Semiconductor (MRS) photodetectors offer the most promise in tackling this issue. The \textit{in situ} use of these photodetectors opens the doors to integration of the full readout chain to an extent that makes a multi-million channel scintillator calorimeter entirely plausible. Also, in large quantities the devices are expected to cost a few dollars per channel making the construction of a full-scale detector instrumented with these photo-diodes financially feasible.

The very large number of readout channels can still pose a significant challenge in the form of complexity and cost of signal transport, processing and acquisition. The development of an integrated readout layer comprised of the scintillator, photodetector and front-end electronics will thus be crucial in carrying the scintillator hadron calorimeter design forward. Research into this integration will be a focal point of our future work described later in this proposal. Simplifications obtained by reducing the dynamic range of the readout may also be part of the solution. Monte Carlo studies have shown that this is indeed possible as scintillator cells with an area in the 6-10 cm$^2$ range are good candidates for one (digital) or two-bit (semi-digital) readout (see Fig. 1) where the lowest threshold is set so as to detect the passage of a minimum ionizing particle. Performance of PFAs on scintillator hadron calorimeter Monte Carlo’s with a minimum of amplitude information in the form of thresholds also looks very competitive [3]. Thus fabrication of cheap and compact electronics with just a few thresholds (three in the case of a 2-bit readout) that will deliver the required performance is a realistic possibility for a scintillator hadron calorimeter.

In these tasks we have been coordinating our efforts with European groups pursuing similar interests. This interaction takes place under the umbrella of the CALICE collaboration [4] which bands together universities and labs, interested in developing calorimeters for the Linear Collider, from all over the world. We are the only group in the United States, actively investigating the promising option of a scintillator-based hadron calorimeter.

\textbf{Status Report}

To date we have received three grants for work related to the project described here. The project titled “Design and Prototyping of a Scintillator-based Hadron Calorimeter” was ini-
Figure 1: Single hadron energy resolution as a function of the incident energy.

Initially submitted as part of the UCLC proposal to NSF in 2003. We were instructed to resubmit, without change in scope, in 2004. The 2003 submission resulted in a $11K NSF “Planning Grant” while in 2004 we were awarded a one year $50K DOE/NSF grant. The LCDRD submission resulted in a $31.5K award for 2005. Please find below a summary of the covered research:

**Tile-Fiber Optimization:** Prototype cells of various shapes, sizes, thicknesses, surface treatments and fiber groovings were machined (see Fig. 2) and evaluated together with fibers of different shapes, dimensions and optical treatments to carry out a comprehensive study of the following:

(a) Cell processing  
(b) Light response  
(c) Response uniformity  
(d) Efficiency  
(e) Cross talk  
(f) Ageing  
(g) Radiation damage

The results of our studies, demonstrating that small scintillating cells are appropriate for a finely-segmented hadron calorimeter, are published in [5] and [6].

**Photodetectors:** We propose to use SiPMs/MRS [7] devices as the photodetectors for the hadron calorimeter. During the course of our investigations we also studied other solid-state photodetectors like APD’s and VLPC’s [8] but find that the SiPMs are the most suitable for the finely-segmented calorimeter we have in mind. SiPMs are multi-pixel photo-diodes
operating in the limited Geiger mode. They have high gain ($\approx 10^6$) but relatively modest detection efficiencies (quantum efficiency*geometric efficiency $\approx 15\%$) and therefore deliver performances similar to (or better than) a conventional PMT. They have a distinct advantage over the conventional PMTs however, due to their small size (1mm x 1mm), low operating voltages ($\approx 30-80V$) and insensitivity to magnetic fields. On the 1mm$^2$ sensor surface there are typically 1000-1500 pixels (see Fig. 3), each one of which produces a Geiger discharge when a photon impinges upon it. The energy is therefore proportional to the number of pixels fired. Typically a minimum ionizing particle (MIP) fires 15-20 pixels (or photoelectrons). Furthermore the small size of the sensors implies that they can be mounted directly on the scintillator tiles (see Fig. 4). This has a number of beneficial effects:

1. **Light Output:** The light suffers little or no attenuation as it does not have to travel large distances in the fiber.
2. **Cost:** The amount of fiber required (WLS or clear) is drastically reduced.
3. **Simplified Architecture:** Since photo-conversion occurs right at the tile one can come out of the detector directly with electrical signals thus largely eliminating the problems associated with handling and routing of a large number of fibers.

During the course of our investigations into these photodetectors the following characteristics were studied in detail:

(a) Working point
(b) Dark rate
(c) Linearity of response
(d) Temperature dependence
(e) Fiber alignment
(f) Medium-term stability
(g) Radiation damage
(h) Immunity to strong B-fields

The results of our studies, showing that SiPMs/MRS are suitable for a scintillator hadron calorimeter, are documented in [9] and [10].
Figure 3: Pixellated surface of the SiPM sensor (left) and photoelectron separation observed with a SiPM (right).

Figure 4: The SiPM sensor (left) mated with a 1 mm WLS fiber and embedded in a 3 cm x 3 cm tile (right).
Test Beam Prototype: The prototyping studies summarized above have pinned down the configuration of the active layers of the scintillator HCal for us. In collaboration with our European colleagues we are now moving towards the construction of a 38 layer scintillator-steel prototype for the testbeam. The proposed prototype, the result of extensive hardware R&D and simulation studies, will address the following overall goals of our program:

(a) Technology demonstration  
(b) Exploration of the full range of readout from purely digital to fully analog  
(c) Validation of hadron shower models in MC  
(d) PFA development

The active layers of the prototype consist of 5 mm thick scintillator tiles sandwiched between 2 cm thick steel absorber plates mounted on a movable table. In reality the absorber is split into three parts: 1.6 cm absorber plate and two 0.2 cm thick top and bottom skins of the “cassette” which houses the tiles. Each tile comes with its own 1mm diameter WLS fiber mated to a SiPM embedded in it. The tiles come in three granularities: 3 cm x 3 cm, 6 cm x 6 cm and 12 cm x 12 cm (see Fig. 5). The 3 cm x 3 cm cells form the inner core for thirty of the 38 layers while for the last eight layers only the coarser granularity cells are used. The granularity of the prototype has been optimized to achieve the goals listed above within a reasonable budget. As the initial proponents of the finer granularity we are responsible for the instrumentation of two-thirds (i.e. 20 layers) of the inner core. A 1 mm thick co-axial cable runs from each photodetector to a charge integrating amplifier channel. This single co-axial cable carries both the bias (on its shield) and signal (on its core). The cables are mounted on a G-10 plate which also has the reflective VM2000 glued to its inner, tile-facing side.

Commissioning: To be ready for beam in time will require an enormous commissioning effort from the collaborating institutions and will make ever increasing demands on our manpower resources. Already in Oct-Nov 2005, we have been involved in the integrated commissioning tests of the HCAL and tail-catcher/muon tracker (TCMT) cassettes in the DESY electron test beam. In addition to verifying the full electronics and data acquisition chain, a few million events were collected which are now being analyzed to better understand the behavior of the devices (see Fig. 6). While extremely useful for exposing HCAL cassettes in ones or twos
the electron beam cannot be used to commission a large fraction of the cassettes together especially when they are inside the stack. Thus efficient triggering on cosmics will be the key to commissioning the approximately 40 layers of the scintillator HCAL. To this end we are fabricating large area trigger counters which will allow the simultaneous commissioning of a large number of HCAL layers.

Current and Planned R&D

Prototype Operation: The scintillator hcal prototype will be exposed to hadron test beams at CERN and Fermilab during the 2006-2007 period [11]. Hadrons in the momentum range 1-50 GeV are of interest. We propose to collect $O(10^6)$ events per setting (energy, angle and particle type) for a total of $\approx 10^8$ events. With $\approx 10K$ channels, the prototype is comparable in channel count to the full calorimetric systems of some of the current collider experiments. Thus a large investment in manpower and resources will be required. Our expertise and location implies that we will be playing a major role in the assembly, commissioning and operation of the prototype. Already one of us (VZ) has been named as one of the two ‘Experimental Contacts’ for the full ILC calorimeter test beam program. Substantial amount of our resources will also be required to calibrate and analyze the data being collected.

The operation of the scintillator-based hadron calorimeter prototype will deliver a wealth of information. It is however clear that R&D will need to continue in parallel to carry the design forward and optimize it for its realization in an ILC detector. The 2-3 year LC test beam program will permit us to make incremental changes to the initial design which can then be tested in the beam without having to assemble an entirely new device. In this regard the major areas of concentration will be:

Electronics Development: A detector consisting of a few million channels requires a high degree of integration. The small size, low bias and magnetic field immunity of the SiPMs has already allowed us to take the first step towards this goal. The photo-conversion occurs right at the tile thus integrating the light transport and conversion functions on the tile itself. The next logical step is to bring an equivalent level of integration to the electrical signal path.
While individual cables per tile are feasible for the prototype containing a few thousand channels, they are not a viable option for a device with a few million channels. Our objective is the design and fabrication of a readout system with the required mechanical and electronics integration such that data from many tiles could be sent off the detector on a few conductors. The strategy is to have a PC board inside the detector which will connect directly to the silicon photodetectors and carry the necessary electronics and signal/bias traces (see Fig. 7). Design and prototyping of this integrated readout board will continue to be one of the key elements of our R&D program for the 2006-07 period. We are undertaking this task with technical assistance from Fermilab electrical and mechanical engineering. Work has already begun on prototyping 1 mm thick, 25 cm x 25 cm PC boards. The board size was chosen as it potentially fits sixty-four (8x8) of our scintillator tiles. For the full detector the most economical solution for the front-end will probably be a custom ASIC which encompasses the following functionalities: preamplification (gain of \(10\)), multiple thresholds (discriminators or time over threshold possible), nano-second time resolution, electronic charge injection and temperature monitoring. For our R&D studies however, we are currently not interested in producing a custom ASIC. The reasons for that are two-fold. First, it is clear that the current funding situation does not allow the development of a custom ASIC to be installed in these boards. Second and even more importantly, a lot can be done before the need for a custom ASIC becomes urgent. Thus a staged approach will be taken. The first boards will not carry any chips. They will carry only the photodetectors and the signal and bias traces. This configuration will allow us to study and optimize the SiPM-PCB interface, signal/bias routing and cross-talk between the traces. Once these boards are functioning satisfactorily, an existing ASIC will be introduced into the board. There are a number of options (e.g. CALICE ECAL and CMS Muon chips) in our hand that serve this purpose adequately and will help us understand power dissipation issues in such an integrated design. The final goal for this R&D will be a few 25 cm x 25 cm planes which can be put in the hadron test beam sometime in 2007.

**Calibration:** The current calibration system relies on transport of LED light through clear fibers to the individual tiles. The LED’s in turn are themselves monitored with a PIN-diode system. For a system with a few million channels this solution can easily get out of hand. Our objective will be the design and prototyping of a robust calibration system which is scalable. We propose to do this by separating the relative and absolute calibration functions. For the absolute calibration we would aim to develop a scheme based on a radioactive source. This may take the shape of a movable wire source or the deposition of radioactive material near the tiles themselves. For a quick monitoring of the gain a LED system may still be useful. The gain of a SiPM can be tracked by monitoring the distance between the photo peaks. Since
only the difference between the peaks is relevant the instabilities in the absolute amount of light emitted by the LED’s is not a critical issue. This obviates the need for a PIN-diode monitoring system. Further simplification may be obtained by shining the LED directly on the tiles. The R&D will focus on the mechanical and electrical aspects of this arrangement. Of special interest on the mechanical side would be the challenge to keep the layer thickness to a minimum while on the electrical side the cross talk induced on the signal traces due to the proximity of the LED will need to be addressed.

**Photodetectors** We will continue to keep abreast of relevant developments in silicon photodetectors. Of special interest to us is the study and characterization of large-area, enhanced blue-sensitivity SiPM’s which are now coming on the market. Their potential value lies in the prospect of a fiber-less operation. The elimination of the fibers from the tile, if at all possible, would significantly simplify assembly of a scintillator HCAL. There are however, very significant issues like optimal tile-photodetector coupling, uniformity of tile response and the extremely high dark rate for large-area SiPM’s that would need to be addressed before any conclusions can be drawn. We have been in negotiations with vendors for the production of a few 3 mm x 3 mm (compared to the 1 mm x 1mm sensors we are currently using) SiPM’s with acceptable room-temperature noise characteristics. If available at a reasonable price we will study their characteristics in detail and assess the possibility of directly coupling these photodetectors to the tiles without the use of a fiber.

**FY2006 activities and deliverables**

1. Commissioning of the Scint. HCAL prototype,
2. Operation of the HCal in hadron test beam,
3. Prototyping of the integrated readout board,
4. Investigation of large-area SiPM’s (if available)

The 2006 deliverable is a prototype accumulating data in a hadron test beam and first results from studies with an integrated PCB design.

**FY2007 activities and deliverables**

1. Continued operation of the HCAL in a hadron test beam,
2. Analysis of test beam data,
3. Installation of a few integrated PCB planes in the test beam,
4. Initiate calibration system design

The 2007 deliverable will be physics results from the scintillator hadron calorimeter prototype test beam run and results of the performance of the integrated readout boards in a test beam.

**Existing Infrastructure/Resources**
The funds requested in this proposal will be augmented by the following support, from other sources:

(a) NICADD personnel,
(b) NICADD scintillator extruder line,
(c) NIU machine shops,
(d) Collaboration with Fermilab on electrical and mechanical engineering.

Budget justification

FY2006: Our participation in the assembly and commissioning of the HCAL prototype will involve NICADD staff members (not included in the budget presented here) and a graduate student (0.5 FTE). The equipment and M&S costs relate primarily to further design and development of an integrated readout (layout, test boards, power supplies, test fixtures etc.).

FY2007: Operation of the test beam, calibration and analysis of the data, testing and installation of the integrated readout boards will be done with the additional support of a post-doctoral associate (0.5 FTE). Support for a graduate student will need to be raised to 1.0 FTE. Fabrication and testing of the boards constitute the equipment and M&S costs.

The travel funds (2006-2007) will cover costs of travel by group members to collaborating institutions and for attending conferences/meetings for the purposes of this project only.

The budget takes into account the NIU mandated fringe: 52% and indirect cost: 45% rates.

Two-year budget, in then-year K$ (NIU)

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Broader Impact

Student involvement in research is a critical aspect of the proposed research program. Students can make significant contributions in detector R&D, construction, testing, software development, data collection and analysis. They are, in the process, exposed to cutting-edge research techniques and technology which they can utilize in industry or related fields.

The scintillator R&D involves collaborative work with chemists and mechanical engineers. As an example, faculty and students from NIU engineering department have been involved in extruder die design and operation. Improvements in this technology are applicable to many fields which need to detect particles including other sciences and medicine.
NIU runs a vigorous outreach program which visits schools and civic organizations in the northern Illinois region with the purpose of increasing enthusiasm and public awareness for science. The presentations emphasize energy and light but also address how scientists make and interpret observations. Over 10,000 students per year attend these presentations. NIU/NICADD faculty and staff also volunteer for the Fermilab 'Ask-a-Scientist' program and a similar one offered through the NIU outreach website.

References

6.2: Study of the Performance of a Scintillator Based Electromagnetic/Hadronic Calorimeter and Study of the BeamCal (renewal)

Calorimetry

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Institution(s)
Colorado

Funds awarded (DOE)
FY04 award: 60,000
FY05 award: 27,000

New funds requested
FY06 request: 306,632
FY07 request: 559,221
STATUS REPORT

Study of the Performance of a Scintillator Based Electromagnetic/Hadronic Calorimeter and Study of the BeamCal

Personnel and Institution Requesting Funding


University of Colorado at Boulder

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Project Overview

We have proposed the design of a scintillator based calorimeter consisting of 5 cm square tiles where alternating layers are offset by $2.5 \times 2.5$ cms leading to an effective granularity of $2.5 \text{ cm}^2$ with a reduction of 4 times the number of readouts. We need to prove that this granularity is sufficient to obtain the resolution needed to separate W's and Z's. Our group is working on the simulation software to carry out this study. We propose that this geometry can also be applied to the hadronic calorimeter. This geometry then would reduce substantially the cost of the detector while maintaining adequate resolution to separate Ws and Zs.

We are also learning how to operate the silicon photodetectors (SPDs) proposed by our Russian and now Japanese collaborators. We are also studying the long time light transmission properties of fibers bent into 2 cm radii. This study is going on and will continue for a year or more.

We have begun, at the request of the Beam-Cal group to help with the design of the Beam-Cal calorimeter for the 20 mrad crossing angle case.

We have made contact with our mechanical engineering faculty to carry out a study of how to build the calorimeter modules with the thin $(0.5 \times X_0)$ Tungsten plates while maintaining their flatness. Lack of funding has kept us from making any progress in this effort.

Status Report

Our group has been working with the SLAC group to learn and use the software being developed. We have written the geometric description of our calorimeter geometry for every one of the detectors (SiD, LCD, GLD) being proposed. This geometry has been installed in the SLAC repository. We are now running GEANT events to develop the parameters that will be used in the calculation of the Chi-Square that would separate the showers produced by the two photons from a $\pi^0$ decay when compared to a single photon of the same energy. This requires producing the covariant matrix elements as a function of the position of the shower in the calorimeter. This work is now going on and will occupy us most of 2006. We expect to produce the Chi-Square separation between a single photon and the two photons from a $\pi^0$ decay for all possible directions and energies of the $\pi^0$. This work is being carried out by the students.

Jason Gray, our graduate student, has written code to trace all charged tracks through the calorimeter and remove their hits in order to clarify the shower patterns. This work is in collaboration with Dr. Milstein from Fermilab. This work will continue and will be used to determine the neutral hadronic interactions both in the electromagnetic and hadronic calorimeters. This work will continue in 2006.

The development of the pattern recognition code to pick up the photon showers and resolve the various single photon contributions needs the participation of a senior research associate dedicated to this problem. The present rate of progress with students is hampered by the amount of time they have available to dedicate to this project.

In January of 2006 we will hold a software workshop meeting in Boulder, Colorado in order to make progress in this effort. The help of the SLAC group in attendance will be of great help to us.

We are developing our expertise in operating the silicon photo detectors (SID). This effort is severely hampered by our lack of electronic engineering help and the lack of available electronic
equipment in our group. We are purchasing equipment slowly within the available funds we have. We have been able to observe very clear signals from the SIDs using a blue diode transmitting light through a fiber but we have not been able to separate the signals from the individual photoelectrons; namely the pulse height analyzer just gives us a single broad gaussian distribution. We are unable to understand why this is the case since our various circuit elements are identical to those used by groups which clearly observe separately the multiple photo-electron peaks. We are working intensely to resolve this problem and this will continue in 2006. Learning how to operate these devices is critical in our effort.

We are studying the light transmission stability of fibers bent in a 2 cm radius. This is a long term project and is proceeding normally. We are including the study of the light transmission in a fiber that has been annealed at temperatures of about 100°C.

We have been requested to help with the design of the Beam-Cal for the 20 mrad crossing. We are beginning to work on this problem to understand how we can detect with very high efficiency the high-energy electron-positron from the two photon process. This is crucial in order to remove a serious background to the SUSY signals. This work is being carried out by our research associate Jinlong Zhang and our student, Paul Steinbrecher. This work is continuing in 2006.

**FY2006 Project Activities and Deliverables**

In 2006 we will continue to develop the software to do the pattern recognition of the photon showers in our electromagnetic calorimeter design. Unless we can get the funding for a research associate this program will develop very slowly and may have to continue into 2007. At the moment this work is being carried out by students.

We will continue to study the long time light transmission properties of a non-annealed and an annealed fiber bent into radii of 2 cms. This study is proceeding and may take 2 years to determine clearly whether the light transmission deteriorates with time. This work will continue into 2006 and 2007.

We will continue to develop our expertise in operating the SPDs. The lack of electronic engineering help makes it difficult to make progress in this effort. This work will occupy my time and that of two students during the first half of 2006. Once we can observe the single photo-electron peak we will proceed to study cosmic-rays to understand the number of photo-electrons observed when a mini-particle (high energy muon) traverses a tile. This work will take place during the rest of the year 2006.

We will initiate in 2006 the simulation effort of the Beam-Cal design for the 20 mrad crossing case.

**FY2007 Project Activities and Deliverables**

The activities in 2007 depend on the funding allocation in 2006 and 2007. If we can not get the support for a research associate and part-time support of an electronic engineer’s time in 2006 the effort in 2007 will consist in a continuation of the effort being carried out in 2006. This implies that in 2007 we will continue to improve our photon shower pattern recognition techniques and will continue to study the SPDs.
If the appropriate funding is allocated in 2006 we will propose to begin the construction of a calorimeter module to take to a beam line and study its resolution and pattern recognition characteristics to compare with our simulation results.

**Budget Justification**

We are requesting full funding of a Research Associate to work on this project and part time support of an Electronics Engineer in 2006 and full time in 2007 if a module is to be built. We have an Electronics Engineer on site working in the JILA complex in C.U. that is interested in working in our project. We are requesting funding for about 50

For students we are requesting funding of one graduate student. Our present graduate student plans to move to our CMS obligations so that he can begin his research towards the doctorate. We would like to hire a graduate student to continue his work. The undergraduates are funded by the University through the UROP and Work Study programs.

The request for this staff funding covers all of 2006. If we need to build a calorimeter module in 2007 we request funding for a full time electronics engineer to help with the electronics design of such a module.

The request for equipment in 2006 is for electronics equipment and to cover the cost of development of extruded scintillator panels (in collaboration with Fermilab).

The fringe benefits for the research associate and electronics engineer consist of 21.6% of salary; for graduate students it is 6.3%. The overhead is 49% of all costs not including equipment or tuition for the graduate student.
### Two-year Budget, in then-year $
### University of Colorado at Boulder

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6.4: Particle Flow Studies with the Silicon Detector (SiD) at the International Linear Collider (ILC)

(renewal)

Calorimetry

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

Institution(s)
Iowa

Funds awarded (DOE)
FY04 award: 50,000
FY05 award: 31,500

New funds requested
FY06 request: 92,499
FY07 request: 0
STATUS REPORT

**Project Name:** “Calorimeter Reconstruction and Particle Flow for the Silicon Detector Concept”

**Personnel and Institution requesting funding**

Matthew Charles, Usha Mallik, and Niels Meyer  
The University of Iowa

**Project Leader**

Usha Mallik  
[usha-mallik@uiowa.edu](mailto:usha-mallik@uiowa.edu)  
(319) 335-0499
Calorimeter Reconstruction and Particle Flow for the Silicon Detector Concept

Matthew Charles, Usha Mallik, and Niels Meyer
The University of Iowa

Usha Mallik’s group at SLAC is working on shower reconstruction for the highly segmented calorimeters of the Silicon Detector Concept. This work is a key component of a Particle Flow Algorithm currently under development with the goal to reach the excellent energy resolution needed for high precision measurements at the International Linear Collider.

1 Introduction

The International Linear Collider (ILC) is the highest priority future large project in particle physics and will complement the expected LHC findings with high precision measurements. To match this physics goal, the detector(s) at the ILC must reach excellent energy resolution of the order of 30%/$\sqrt{E}$ [1].

Several detector concepts have been proposed. Three of these were discussed in detail at Snowmass 2005: the Large Detector Concept (LDC) [2], the Global Large Detector (GLD) [3], and the Silicon Detector concept (SiD) [4]. Each of these three assumes that the anticipated resolution can only be achieved by reconstruction of individual final state particles using a Particle Flow Algorithm (PFA). Of the three, the SiD uses the most fine-grained detectors: a high precision silicon tracker, a Silicon-Tungsten sampling electromagnetic calorimeter (ECAL) with approximate cell size 4mm×4mm, and a hadronic calorimeter (HCAL) with approximate cell size 1cm×1cm¹.

In this proposal, we describe the corner stones of a PFA for the SiD, the contributions of our group towards its realization, and the status of our various projects. Only the immediate goals for this year are described; these are critical to achieving a realistic detector design.

¹The final HCAL technology for the SiD has not yet been chosen; RPC-, GEM-, and scintillator-based detectors are being considered.
2 Particle Flow Algorithm

Energy deposition in calorimeters occurs via statistical processes. In general, the physics of electromagnetic showers is well-understood and shower development can be modelled straightforwardly. For photons and electrons of a given energy, there is a good degree of consistency across showers in the Silicon-Tungsten SiD ECAL, both in terms of the shape and of the total energy deposited in the active elements. By contrast, hadronic showers are more difficult to model and display a great deal of variation in structure; the energy resolution of hadronic showers in the SiD projective RPC calorimeter is expected to be significantly worse than that of electromagnetic showers in the ECAL [5]. A more accurate way to measure the energy of charged hadrons is to use momentum information from the tracker and a particle ID hypothesis. For the limiting case of an algorithm with perfect pattern recognition, the jet energy resolution is then dominated by the neutral hadron energy resolution.

In practice, the resolution is also degraded by an imperfect algorithm assigning charged energy to neutral particles and vice-versa: this is often referred to as the “confusion term” in the energy resolution. One of the main goals of a particle flow algorithm is to minimize this confusion term. This is only possible if individual particles within jets can be resolved, which in turn implies a high-granularity (imaging) calorimeter. The precision of the detector will increase the experimental challenges (e.g. large numbers of channels, calibration, and noise). A realistic PFA is essential to explore the mutual dependencies between detailed detector design, technical issues, costs, and the final energy resolution, and to guide the concept towards a final design optimized for physics output.

There are many technical challenges to achieving such good resolution: hardware, software, and algorithmic. One year ago, the SiD collaboration had barely the beginnings of a PFA. Since then there has been tremendous progress: implementations of many of the components are now available such that Steve Magill of ANL was able to present Z–pole results with a proof-of-concept PFA at Snowmass [6]. The challenge is now to develop and tune a PFA which takes full advantage of the fine granularity and which reaches the target energy resolution in high-multiplicity events at a center-of-mass energy of 500 GeV and above, and which is sufficiently general to allow comparisons of different detector designs.
3 Status Report

Substantial improvements in the PFA implementation are expected from more advanced calorimeter reconstruction techniques, where the Iowa group has built up competance since 2003. Through 2005, the post-docs Matthew Charles, Wolfgang Mader and Niels Meyer have contributed to the project, sharing their time between the Linear Collider effort and the group’s commitment to the BaBar experiment at SLAC. Niels joined the group in February after graduating from the University of Hamburg; Wolfgang will leave the group in December.

3.1 Software Tools

In order to undertake detailed studies of cluster structure, it is essential to have algorithms which can identify general patterns such as track segments or dense energy deposits. In the previous proposal, work by Wolfgang on minimum ionising particle (MIP) segment finding was reported, including reconstruction of long-lived $K^0_S$. A preliminary version of a Minimum Spanning Tree (MST) clustering algorithm was also described; this takes as input a metric providing a definition of distance between two hits, and then clusters hits according to a threshold parameter on this distance. Since then, Wolfgang has formalized the code for both the MIP-finding and MST algorithms and committed it to the hep.lcd CVS repository.

Upon joining the group in February, Niels began by updating and generalizing the MST interface so that it could combine not just individual hits but also clusters, in anticipation of the need to associate secondary neutrals and other fragments with their parent cluster. He also added a generalised decision-maker interface for more flexible steering and user interaction.

Niels and Matthew have also worked to convert the existing code to the new org.lcsim software framework. This is essentially complete for the MST and track segment finding algorithms, as well as the decision-maker interface. The code is available in the org.lcsim CVS repository. Matthew is currently adding his structural algorithm (see Sec. 3.4) and has begun contributing to the SLAC group’s work on geometrical routines (principally the two-way conversion between calorimeter cell channel ID and spatial location) which are still missing in the new software framework.
Figure 1: The mean number of clusters per $Z^0$ event as a function of the minimum number of hits $n$ in the cluster, for (a) the ECAL, (b) the HCAL. The first trace shows the number of reconstructed clusters with at least $n$ hits in the calorimeter; the second trace shows the number of MC particles with at least $n$ hits in the calorimeter, extracted from truth information. The excess of reconstructed clusters at small $n$ is primarily due to a large number of small secondary clusters.

3.2 MST Studies with $Z$-Pole Events

The MST algorithm links contiguous groups of hits into clusters if the three-dimensional distance between hits is used as its metric. This is particularly effective for hadronic clusters, which frequently have many secondary tracks emerging at wide angles; a simple cone-based clustering method would have reduced efficiency in such cases.

Wolfgang studied the MST with this metric in detail using hadronic events simulated at the $Z$-pole. The threshold parameter of the algorithm is varied, and output clusters with at least $n$ hits are identified as cluster cores, the leading contributions of a shower. By comparing the reconstructed and expected number of cluster cores, see Fig. 1, the optimal combination of threshold and minimum size of a cluster core was obtained for the electromagnetic and the hadronic calorimeters (3 cm and 5 hits for the ECAL, and 10 cm and 8 hits for the HCAL). The results from this study were presented at the LCWS workshop at SLAC [7].
3.3 Electromagnetic Showers

Niels studied the reconstruction of electromagnetic showers, starting with the MST algorithm and parameters obtained as described above. Photons were identified with a simple selection based on cluster size, shape, composition and position in the calorimeter. The selection is tuned to accept one cluster per shower, as shown in Fig. 2a.

The efficiency and purity of electromagnetic clusters reconstructed in $K_S \rightarrow \pi^0\pi^0$ events were studied. Because the photon clusters are typically close to one another, it was found that a large value of the threshold parameter (e.g. 3 cm, as obtained for hadronic $Z$-pole events in the ECAL) results in reduced purity: clusters frequently contain energy deposits from two different particles, even in cases where the showers could easily be separated by eye on an event display. Furthermore, these merged clusters are inconsistent with a single-photon shower and therefore fail the shape cuts mentioned above, leading to a low efficiency. On the other hand, a very small threshold value results in improved purity at the expense of energy collection efficiency. The solution is a reconstruction in two passes: Identifying the shower cores with a very tight MST threshold, and assigning remaining energy deposits (fragments) to the cores.

Using this approach, it has been shown that showers from two photons can be resolved if the separation between the photons at the calorimeter surface is 3cm or more (see Fig. 2b). The cores found in this way contain the majority of the total energy deposition, as illustrated in Fig. 2c. Currently, strategies to enhance the energy collection efficiency based on a two dimensional distance definition between fragments and the principle axis of the shower core are under study. Preliminary results, produced in the hep.lcd framework, were presented at Snowmass in August 2005 [8, 9].

3.4 Hadronic Showers

Reconstruction and identification of hadronic showers is central to the PFA approach. There is a great deal of variation between individual showers: designing a general algorithm to reconstruct them is not straightforward. Matthew and Usha began to tackle this problem by studying a number of single-particle and low-multiplicity events in detail, attempting to understand their structure in such a fine-grained detector. Based on their observations, Matthew developed the following method.

The components of hadronic clusters may be categorized as (a) dense clumps, (b) track segments, (c) a halo of less dense hits following a hard
Figure 2: Performance of the photon-finder in a sample of $K_S \rightarrow \pi^0 \pi^0$ events. Plot (a) shows the difference between the number of photons produced and the number reconstructed. Plot (b) shows the ratio of reconstructed clusters to actual photons as a function of the photon separation on the calorimeter surface. Plot (c) shows the fraction of the energy recovered when a core is found.

interaction, and (d) displaced secondary fragments. Code based on the MIP-finder and MST tools was written to identify components (a) and (b), and a cut-based selection was developed to determine whether a given pair of components were directly linked. By linking together these basic components, the “skeletons” of hadronic showers are reconstructed; components (c) and (d) can then be added to recover the remaining hits. In this way, hadronic showers can, in principle, be reconstructed with high efficiency and purity even in very dense environments. Preliminary results from this algorithm, produced in the hep.lcd framework, were presented at Snowmass in August 2005 [10, 11].

After Snowmass, the algorithm was revised to use a likelihood selector to identify correct (or incorrect) links in the place of the cut-based selection. Further geometrical criteria were also added to the selector. In order to assess the algorithm’s performance, modular code which used truth information (i.e. cheating) at each stage of a full PFA was written. The performance when using truth information throughout was evaluated on a sample of approximately 400 hadronic $Z$-pole events simulated for a version of the SiD detector with a sampling scintillator HCAL. The (non-cheating) reconstruction algorithm for identifying and linking components (a) and (b) was then substituted for the corresponding module and the performance re-evaluated on the same sample of events. The result, an energy sum distribution with RMS 3.4 GeV, was—within the statistics—indistinguishable from the energy resolution achieved when using the full truth information.
Adding a simple, non-cheating module to associate the fragments in categories (c) and (d) without using truth information worsened the resolution to an RMS of 4.3 GeV. These results, produced in the hep.lcd framework, were presented to the SiD group in September 2005 [12] and are shown in Figure 3.

The algorithm has now been converted to the org.lcsim framework; this required rewriting the bulk of the code. Several new features have been added in the process to make a complete PFA; in particular, charged tracks are now matched to clusters in a much more realistic fashion, extrapolating helices from the interaction point and looking for a consistent track segment near the entry point to the ECAL (or, failing that, another nearby cluster). A status report was presented to the SiD group in November 2005 [13], including preliminary results from the likelihood selector which are shown in Figure 4. Initial energy sum plots look promising, but the code is still being debugged and tested.

From the results obtained since Snowmass, this method of reconstructing hadronic clusters seems promising, and performed well at finding and identifying the main body of the clusters in hadronic Z-pole events. The critical challenge—for this and other clustering algorithms—will be the association of fragments, principally secondary neutrals. This is where effort will be focused next, using experience and tools from the algorithm described above.

4 Future Plans (Deliverables)

The next steps will be to improve and extend the algorithms presented in sections 3.3 and 3.4. Code to assign fragments to nearby cores will be developed both for electromagnetic and for hadronic showers. The different algorithms will then be integrated into a single PFA with the following general structure:

1. Find the cores of electromagnetic showers
2. Make initial assignments of fragments to the electromagnetic cores
3. Find the core components of hadronic showers and link them (where appropriate) to form cluster skeletons
4. Make initial assignments of fragments to the hadronic showers
5. Extrapolate charged tracks to the calorimeter surface and associate them with clusters
Figure 3: Energy sum plots for Z-pole events, showing (a) the reconstructed energy sums without cheating, and (b) the reconstructed energy sum for a PFA with perfect pattern recognition. The true energy sum is 91.0 GeV, but the correct sampling fractions were not available for this simulated detector; as a result, the overall energy scale is off and the resolutions are worse than could be achieved with full calibration. The RMS values correspond to $37\%/\sqrt{E}$ for (a) and $45\%/\sqrt{E}$ for (b).
Figure 4: Likelihood distributions for links between components of hadronic clusters, obtained in a sample of hadronic $Z$-pole events.
6. Refine the assignment of fragments and hadronic components (especially if the assignments are ambiguous, or if the energy of a charged cluster is inconsistent with the track momentum)

Once this is accomplished, additional steps to further improve the algorithm will be considered—for example, handling of $K_S$ and other long-lived particles, merging of $\gamma$ pairs into $\pi^0$s, and using event information to improve the cluster assignments iteratively. Throughout the development, an important goal is to keep the algorithm as general as possible so that it can be applied to other detector designs.

5 Resources and Budget

The group has devoted the effort of 1.5 post-docs to the Particle Flow Algorithm for the SiD concept, described in the proposal. Last year the financial support to the Iowa group (Task A) for ILC R&D in the form of a supplement was $31,500 ($50,000 the year before). The base program of the group working on the BaBar experiment has historically been supported with two post-docs (and students). In anticipation of the level of ILC activity, and the increased necessity to establish a PFA, the group had hired Dr Wolfgang Mader in early 2004; he could not be supported beyond December 2005, and is leaving. The ILC activity at the current level has so far been supported by the base program primarily. This is not practical any longer. A minimum personnel support of one post-doc is needed to sustain the R&D activity of the group to maintain the steady and continuous progress. The rest (half a post-doc) can be supplied from the base funding. Additionally, there are frequent regional workshops and a few LCWS meetings where travel is necessary for active workers. Travel for the post-docs and the PI to some of these is included. The total estimated cost includes 32.7% fringe benefit for the personnel, travel and 26% off-site indirect cost rate, and is explained in detail below.

References


[5] J. Repond, SiD Calorimeter Overview,  
Presentation at the 2005 International Linear Collider Physics and Detector Workshop, Snowmass, Colorado, 14-17 Aug 2005.

[6] S. Magill, PFA Development for a LC Calorimeter,  
Presentation at the 2005 International Linear Collider Physics and Detector Workshop, Snowmass, Colorado, 14-17 Aug 2005.


[8] N. Meyer, Electromagnetic Showers with the MST Algorithm,  
http://zebu.uoregon.edu/~rayfrey/LC/SiD-cal_Snow05/meyer.ppt  

[9] N. Meyer, Electromagnetic Showers with the MST Algorithm,  
https://wiki.lepp.cornell.edu/wws/pub/Projects/CalIowaPfa/niels-20050822-Snowmass.pdf  

[10] M. Charles, Dissecting the Structure of Hadronic Clusters,  
http://zebu.uoregon.edu/~rayfrey/LC/SiD-cal_Snow05/mcharles.pdf  

Presented at the Particle Flow Algorithm session, 2005 International

[12] M. Charles, Status of Particle Flow Studies, 
http://www.slac.stanford.edu/~mcharles/talks/ 
Presented to the SiD Calorimetry group, 21 Sep 2005.

[13] M. Charles, Update on cluster association algorithms, 
http://www.slac.stanford.edu/~mcharles/talks/ 
2005-11-17.pfa/slides-mcharles.pdf 
Presented to the SiD Calorimetry group, 17 Nov 2005.
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  - Trips: 2
  - Persons: 1
  - Days: 3
  - Air fare: 750 /trip
  - Subsistence: 150 /day
  - Car rental: 50 /day
  - Registration: 300
  - **Subtotal**: 3,300

- Attendance and participation in summer scientific conference for Post-doc and PI
  - Trips: 1
  - Persons: 2
  - Days: 7
  - Air fare: 750 /trip
  - Subsistence: 150 /day
  - Car rental: 50 /day
  - Registration: 300
  - **Subtotal**: 4,550

#### Foreign:
- Scientific collaboration at Bangalore, India
  - Trips: 1
  - Persons: 1
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**Total Travel**: 11,970
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**Total Other Direct Costs**

|                                                   | 400        |

### TOTAL DIRECT COSTS

|                                                   | 73,412     |

### FACILITIES AND ADMINISTRATIVE COSTS

26% of Modified Total Direct Costs (MTDC) for off-campus research activities, per rate agreement negotiated with DHHS.

| Total Direct Costs                               | 73,412     |
| Less Exclusions                                  | 0          |
| MTDC                                            | 73,412     |

F&A Rate 26.0%

| F&A Costs                                       | 19,087     |

### TOTAL ESTIMATED COSTS

|                                                   | 92,499     |
6.5: Development of a silicon-tungsten test module for an electromagnetic calorimeter

(renewal)

Calorimetry

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

Institution(s)
Oregon
SLAC
U.C. Davis
BNL
LAPP - Annecy

Funds awarded (DOE)
FY04 award: 55,000
FY05 award: 40,000

New funds requested
FY06 request: 68,000
FY07 request: 71,700
STATUS REPORT

Development of a Silicon-tungsten Test Module for an Electromagnetic Calorimeter

Personnel and Institution(s) requesting funding

University of Oregon, Department of Physics and Oregon Center for HEP:
Jim Brau (faculty), Raymond Frey (faculty), David Strom (faculty), physics undergraduate(s)

University of California, Davis, Department of Physics:
Richard Lander (faculty), Mani Tripathi (faculty), Britt Holbrook

Collaborators

Stanford Linear Accelerator Center:
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Project Overview

The current LDC and SiD detector design concepts call for a silicon-tungsten (Si-W) electromagnetic calorimeter (ECal) as the best option for providing the necessary density and segmentation to implement the particle flow method (PFA) for reconstruction of jets (and taus) at the LC, capable of achieving jet energy resolution of \( \approx \frac{0.3}{\sqrt{E_{\text{jet}}}} \), as recommended by LC physics studies. One of the outstanding technical questions is how to integrate a silicon detector wafer with its readout electronics. Since the number of detector pixels for these ECal designs is on order 50 million, a solution to the integration issue, along with the cost of the silicon detectors themselves, is likely to determine the overall viability of the Si-W approach. A few years ago, we proposed[1, 2] a possible solution to the integration problem and have received LCRD support for three years to pursue this. The integrated approach also provides a design which naturally allows high transverse segmentation (currently 3.5 mm) and a small readout gap (currently 1 mm) to maintain a small Moliere radius.

During the past year we made important progress. The design of the readout chip (named KPiX) was completed and was sent to industry for prototype fabrication. This effort was led by SLAC. We have made progress characterizing the prototype silicon detectors at Oregon. A group at UC Davis has joined the effort and their budget request is included in this year’s proposal. Davis has
developed a novel readout cable concept which will help maintain the thin readout gap. They will also provide the bump bonding at Davis for the initial prototypes. Our work gives us confidence that we are on the right path and we propose for the next year to complete the initial phase of the R&D — to demonstrate the detector concept with prototypes in an electron test beam — and to move on to the next phase: The development of a full-depth ECal module which incorporates the features required for a realistic LC detector. This module could be part of an international test beam study. The full-depth module requires more funding than is realistically available with the present LCRD program. Hence, the required additional funding is being pursued separately. Here, we focus on completing the development and initial testing of the detector components, the goal being to test a few layers of our prototype detectors and electronics in the lab at Oregon and in an electron beam, hopefully at SLAC.

While we focus on an implementation of our Si-W approach for the SiD design, the basic ideas and R&D are certainly applicable to other Si-W ECal designs, notably LDC.

The thrust of our project is to integrate detector pixels on a large, commercially feasible silicon wafer, with the complete readout electronics, including digitization, contained in a single chip which is bump bonded to the wafer. The starting point for our design uses a pixel size of 12 mm\(^2\), based on initial PFA requirements for photon-hadron separation. This gives \(N \approx 10^3\) pixels per 6-inch wafer. We take advantage of the low beam-crossing duty cycle (\(\sim 10^{-3}\)) to reduce the heat load using power cycling. This scheme has several important properties:

1. The electronics channel count is effectively reduced by a factor \(N\).

2. A transverse segmentation down to a few mm can be naturally accommodated.

3. The cost, to first order, will be independent of the transverse segmentation.

4. Readout gaps can be small (\(\sim 1\) mm), thus maintaining the small Moliere radius intrinsic to tungsten.

The first property, we feel, is necessary for any realistic highly-segmented ECal. In this case, the electronics is likely to be a relatively small fraction of the ECal cost. The third point makes the design flexible, so that one can optimize to meet the physics goals. The fourth is an optimization of the physics capability of the ECal at a given (barrel) radius. For example, the angle subtended by the Moliere radius for an ECal at radius 1.25 m with our design is smaller than one with 3mm readout gaps at 1.7 m. Hence, this has a significant impact on both performance and overall detector cost. We note that for a Si-W ECal, the features above remain unique to this R&D.

Our R&D collaboration has been holding weekly meetings by telephone for over three years. Although there is significant mixing, the responsibilities within the collaboration break down as follows:

SLAC: KPiX readout chip design, procurement, and testing.

Oregon: Silicon detector design, procurement, characterization, and testing.

Davis (new): Readout cable design and bump bonding of prototypes.
In addition, Veljko Radeka at BNL has provided critical advice and review of the electronics design and implementation plans. Recently, the Annecy group led by Yannis Karyotakis has begun working with us on the mechanical design, both for the prototype and for the final calorimeter. The funding for the Annecy R&D is being pursued separately. Oregon and SLAC plan to continue related simulation and software activities. These include, but are not limited to, EGS4 and Geant4 studies, comparisons between the two, and development of PF algorithms. Ultimately, we will use robust PFA results to optimize the calorimeter. This effort has strong ties to the Calorimeter Working Group of the ALCPG and to the Calorimeter group within SiD. We report regularly to these groups in regular telecons and at the workshops. Many of the details not presented here are collected at http://www.slac.stanford.edu/xorg/lcd/SiW/ or in the cited references.

We are very aware of the separate Si-W ECal effort within the CALICE R&D collaboration. We note that the goals of the two efforts are considerably different. While we are pursuing R&D to develop detectors and electronics which we feel will closely resemble the final ECal, the CALICE effort has focused more on gaining experience with detector fabrication and in developing a working test beam module. In addition, the technical implementation of Si-W taken by the two efforts differs significantly. Since both of these approaches are important, it is premature, and probably counter-productive to merge efforts at this stage. In the meantime, we share our thoughts and concerns. The level of collaboration will increase as we approach full-module test beam studies. Following full-module tests, one expects the two R&D efforts to merge.

**Status Report**

The most significant development for our project in 2005 was the completion of the design of the KPiX readout chip and the submission of the design to industry for fabrication of a first round of prototype chips to be tested. However, since no LCDRD funding is requested for this activity, we do not report on it here. A recent discussion of the KPiX functionality can be found in Ref. [3]. The following summarizes the progress during the past year on silicon detector R&D centered at Oregon and roughly follows Ref. [4]. This is followed by a discussion of the proposed R&D from the the UC Davis group.

**Progress at Oregon**

In 2005 we continued measurements on the 6 inch Hamamatsu prototypes with particular emphasis on parameters relevant to use of the sensors with electronics designed for the cold ILC design. The most important measurements in this regard are the measurements of stray capacitance and leakage current. We have also investigated the use of a radioactive source for an absolute calibration. The results here are an update of our presentation[4] at LCWS05.

**Pixel Capacitance and Trace Resistance**

In almost all cases the noise of an individual pixel charge measurement in our detector will be directly proportional to the total capacitance seen at the input of the amplifier. The capacitance of a fully depleted 5 mm pixel in detectors 325 $\mu$m thick, is expected to be approximately 5.3 pF.
Figure 1: Example traces with varying amounts of stray capacitance. In the prototypes the $r = 6.75$ cm.

The majority of the capacitance is due to the stray capacitance of the traces which connect the individual pixels to the bump-bonding array.

For the Hamamatsu process used in our detectors, the thickness of the oxide to the second metal layer is approximately 0.9 $\mu$m. In our detector we used 6 $\mu$m thick traces, giving a theoretical capacitance of approximately 3.1 pF/cm. The total amount of stray capacitance associated with a given pixel has two contributions. One contribution comes from the capacitance of the traces connecting the pixel to the bump-bonding array. The second contribution is due to any traces from other pixels which cross the pixel under test. The total stray capacitance is almost constant for many of the pixels as can be seen from Figure 1. In region $a$ it can be seen that pixels located closer to the bump-bonding array have a greater number of crossing traces than those further away. This gives an almost constant total measured (and calculated) stray capacitance. Typical stray capacitances in region $a$ were $\sim 22$ pF. An example run is shown in Figure 2.

A small fraction of the pixels have a very large number of crossing traces. These pixels are located in regions $b$ and $c$ of Figure 1. For the first prototypes these pixels have capacitances of somewhat more than 100 pF. In a future version of the sensors we plan to reduce the stray capacitance in region $c$ by narrowing the traces in the vicinity of the bump-bonding array. In Figure 3 the measured capacitances are shown for a large number of pixels in one quadrant for the Hamamatsu detector. In Figure 4 the expected capacitance for a future version of the detector with 1024 pixels and slightly smaller pixels is shown.

Another important property of the detectors is series resistance of the traces. The noise contribution from this series resistance is proportional to $C_{tot} \sqrt{R_s}$ where $C_{tot}$ is the total input capacitance.
and $R_s$ is the series resistance. The contribution to the noise from the input FET in a charge amplifier is proportional to $C_{tot} \sqrt{\frac{2}{3g_m}}$ where $g_m$ is the transconductance of the input FET. Thus it is desirable to keep $R_s$ comparable to $\frac{2}{3g_m}$. In our case we expect $\frac{2}{3g_m} \sim 300\,\Omega$.

Based on the measurement of one of the trace’s resistance, we obtain a trace resistance of $57 \pm 2\,\Omega/cm$. This can be compared to an expected value of $47\,\Omega/cm$ for a pure aluminum traces $1\mu$m by $6\,\mu$m. For the longest traces, of order 10 cm, the measured value implies a maximum resistance of $570\,\Omega$.

It would be desirable to reduce this trace resistance by making thicker traces, however, it is unlikely that the thickness can be increased much beyond its current value of $1\mu$m. Increasing the width of the trace is not helpful because it will increase the component of $C_{tot}$ from the traces connecting the pixels to the bump-bonding array almost linearly. Except in the region the near bump-bonding array, our trace width of $6\,\mu$m is close to optimal.

**Leakage Current**

Leakage current can add an additional term to the electronic noise that grows with shaping time. Typical leakage currents in silicon pad detectors, such as the prototypes used here, have currents of a few nA/cm$^2$. The leakage current was measured during the capacitance tests and was found to be less than $2\,nA$/pixel for pixels in the interior of the detector. In our tests the neighboring pixels
and the guard ring were left “floating.” For pixels on the edge of the detector, with the guard ring floating, the leakage current was less than 10 nA/pixel, see Figure 5. We expect the noise contribution for leakage current to be minimal; the expected contribution for a leakage current of 10 nA and an integration time of 1 µs is only 250 electrons.

Calibration

Calorimeters based on silicon are expected to be quite stable over time. The largest changes in calorimeter response will be due to changes in the electronics. The readout electronics are being designed with an internal calibration system that allows a wide variety of charges to be injected into each of the channels in the system. The accuracy of this system is expected to be limited by the knowledge of the values of the coupling capacitors incorporated into each of the channels in the readout chip. These capacitors are expected to be uniform, within a chip, with a spread of ~ 1%. This spread is unlikely to have a noticeable contribution to the energy resolution of the calorimeter. Chip-to-chip variations could be larger.

One possibility is to calibrate each sensor after the readout chip has been bump bonded. A possible method for this calibration would be to use 60 keV photons from the decay of radioactive Am^{241}. If the energy from these photons are fully contained in the silicon sensors they will give
a signal of approximately 16,000 electrons. This is somewhat less than the MIP signal, but well above our noise floor.

The 60 keV photons will easily penetrate any mounting structures and printed circuit boards used in the testing and assembly of the calorimeter. However, the calibration must be done before the detector assemblies are placed between the tungsten sheets, as the photons will not efficiently penetrate the tungsten. We have used our laboratory electronics to measure the energy spectrum from the Am$^{241}$ photons in the pixels as shown in Figure 6. The widths of the peak is consistent with the expected electronic noise.

As a demonstration of this technique we show the value of the photon Am$^{241}$ peak versus pixel capacitance in Figure 7. The peak shifts to lower values at large values of the capacitance because of the finite input capacitance of laboratory electronics. The line corresponds to a "dynamic" capacitance of our laboratory electronics $C_{\text{dyn}} \sim 790$ pF which is consistent with the laboratory amplifier’s specifications.

In the readout chip planned for the final detector, the signal-to-noise for Am$^{241}$ peak will be about 8, which will broaden the peak considerably. Another important aspect of the planned readout electronics will be that a measurement of the charge will be done relative to an external bunch clock rather than relative to the time of arrival of the photon as was done in the laboratory. This will lead an additional smearing of the observed spectrum of less than 5%. Thus we expect a total width for the Am$^{241}$ 60 keV signal of approximately 15%.

The ADC in the planned detector readout will have a least significant bit approximately equal to the expected noise. Therefore, if there were no systematics in the ADC it would be possible to calibrate each pixel to 1% with approximately 250 detected photons. For this calibration to be useful it will be necessary to relate the charge scale at 8 ADC counts to that at full scale readout. This is possible, but will require great care in the design of the calibration circuit on the readout chip.

Somewhat easier, but still difficult, will be a wafer-to-wafer calibration at the sub-percent level. Here one can average over 1024 pixels/wafer. Again it will be necessary to relate the average charge scale at 8 ADC counts to the average full scale readout.

Cross Talk

We are continuing to study cross talk introduced by capacitive couplings between the channels. In general these have lead to cross talk at the 1% level or below. The cross talk is function of both the capacitive coupling and the properties of the readout electronics. While we have a qualitative understanding of the cross talk, we are continuing to work on a quantitative model and on incorporating the properties of the KPiXs electronics into the model.

UC Davis Proposed R&D

The device discussed above consists of interspersed layers of a radiator (W) and a sensor (Si) which together form a sampling calorimeter. The sensor layer is composed of a set of hexagonal silicon diode wafers tiling the surface of a large W panel. Each wafer is divided into pixels, the pickup
pads of which are connected by traces to an array of contact pads. The ASIC readout chip contains unit cells of electronics arranged in an array that matches that on the wafer. The connections between the array of sensor pixel traces and the array of readout cells are made by flip chip bump bonding of the ASIC to the sensor wafer. Communications between the ASIC and the readout system located at the periphery of the calorimeter are also accomplished via pads located on the sensors. These pads will connect with buses made out of flexible kapton cables. UC Davis will carry out the following tasks:

Bonding of readout chips to the sensor wafers. To do so, we will use photolithography techniques to form the appropriate array pattern in the center of a sensor wafer. In a separate process, a readout chip will have a similar pattern placed on it. Under-bump metallization will be sputtered onto each array. This will take place in the Microfabrication Facility on the Davis campus. Indium will then be evaporated onto the wafer and also onto the readout chip in our own physics laboratory. After liftoff of the photoresist, the wafer and readout chip will have on them matching arrays of indium bumps. The flip chip bonding will then take place using a Research Devices M8HP bonder at UCD. Here, the two indium arrays are precisely aligned in the bonder and pressed together to form a cold weld of indium to indium. The process will be repeated for many wafers and chips, and the result will be a set of sensor/readout units that will be used to tile the SiW layer. We have used this procedure for many individual readout/sensor bondings, in particular for all of the prototype CMS Forward Pixel Detector units. Indium bonding is also being used by the Paul Scherrer Institute group for the CMS barrel pixel detector.

Design and Fabrication of flexible cables. The array of sensor plus readout chip units in a given layer will need to be controlled and read out by electronics that will reside on the periphery of that layer. In order to achieve the best possible energy resolution in the calorimeter, the gap between layers needs to be minimized. The present design calls for a gap thickness of 1 mm or less. We are proposing to use a flex cable technology for the data and control bus and some form of bump
bonding to connect the cable to pads located on the silicon wafer substrate. The cable will most likely be at least 4 layers with 2 shielding/power layers and vias that connect to traces running along 2 buried layers. A need for placing bypass capacitors on the cable is also foreseen if they can be accommodated without increasing the overall thickness substantially. We will design this cable at UCD using the Mentor Graphics/PADS software package and have them fabricated by an outside vendor. The testing of the cable will take place at UCD using our probe station. The group has fabricated a similar cable for the CDF experiment and has experience in designing dozens of circuits using PADS.

**FY2006 Project Activities and Deliverables:**

- Receive KPiX prototype chips and evaluate functionality (mostly at SLAC).
- Complete evaluation of first round of prototype detectors (Oregon).
- Develop and fab. first kapton flex readout cable (Davis).
- Design 2nd round of detectors to be used in full ECal module (Oregon, SLAC, Davis).
- Design concentrator boards (digital boards downstream of KPiX) (SLAC).
- Prepare for mounting of 1st round KPiX prototypes to 1st round detectors (Davis, Oregon, SLAC).
- Mount (bump bond) about 10 KPiX to detectors (Davis).
- Develop mechanical design for full ECal module (Annecy, SLAC, Oregon).

**FY2007 Project Activities and Deliverables**

- Carry out full tests of a few layers in lab and electron beam at SLAC of KPiX-detector prototpyes (Oregon, SLAC, Davis).
- Mount (bump bond) KPiX to 2nd round detectors for ECal full module (Davis).
- Carry out mechanical and magnetic field tests of KPiX + detectors (Oregon, Annecy, SLAC).
- Order full 1024-channel KPiX chips (SLAC).
- Fabricate full ECal module (all).
- Put full module in electron beam at SLAC for determination of EM response and resolution (all).
We are considering as many as three beam tests. The first is a “technical” test (early FY2007) of 1-2 layers (i.e. one layer ≡ one detector with one readout (KPiX) chip). Next, we would test the full-depth ECal module in an electron beam, presumably at SLAC, to fully map out electromagnetic response and resolution. Hopefully, this will occur in FY2007. Finally, we would put our module plus an LC HCal module into a hadron beam, probably at FNAL, to determine hadron response and validate the GEANT4 simulation codes upon which the design of a full detector relies. There are currently several possible scenarios for this test. The validation of the simulations will presumably be aided by using detectors (ECal and HCal) with fine segmentation, hence there would be an important role for our module in such tests.

Taking into account damage, lab tests, and so forth, we will need to procure about 40 new silicon detectors for the full-depth ECAL module. We estimate the cost, based on our previous order, to be about 200k$, about 35% of which would be NRE for the photomasks. Hence, Oregon is seeking 50k$ over two years in this proposal and the remaining 150k$ outside of the LCDRD process.
In the following, we present the Oregon budget and justifications, then the Davis budget and justifications, followed by the total project budget.

**Oregon Budget justification:**

We request lab test equipment and supplies, partial funding for prototype detectors (see discussion above), and undergraduate wages to carry out our program.

As discussed above, we request a total of 50k$ over two years for the detectors for the full module. This is to be supplemented by 150k$ requested separately.

For the technical beam test we request 5K$ for the design and fabrication of mechanical fixtures.

Lab test equipment request includes the following: Low and test amplifiers (2k$), clean room supplies (2k$), and an FPGA card (2k$) for the back-end readout.

For the development of our printed circuit motherboard for the first beam test we request 4k$ for its design, 4k$ for its fabrication, and 2k$ for the required wire bonding to the KPiX chip. Note that the Davis flex cable will eventually replace functionally replace this.

Travel includes test beam related shipping in addition to some travel to LC workshops.

We currently employ an equivalent of two undergraduate physics students in our R&D at the level of 10 hours per week. We request support for 40 weeks per year of support for each of two students, at hourly wages of $8/hour with no fringe benefits. Including indirect, this is about 10 k$ per year.

The indirect rate is 26%. Indirect is not applied to equipment for items costing more than 5k$. So we assume no indirect is applied to the silicon detector orders. Otherwise, the numbers given above include indirect, so are 26% larger than the ones in the table below.

The item for PC board development included in last year’s proposal, is now, in part, transferred to UC Davis under flex cable development.

**Oregon two-year budget, in then-year k$:**

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UC Davis Budget justification:
For the bump bonding and flex cable development, we will need two technicians (0.25 FTE each). The expertise required for the two tasks is vastly different and it is unlikely that one Tech would be trained in both. Based on present experience, the personnel costs, spread over the two years, are estimated to be 8.0k$ for the bump bonding (at 0.25 FTE) and 12k$ for the flex cable (at 0.25 FTE). Fringe benefits are included in these figures.

We assume that there will be 40 wafer/readouts to be bonded during 2006-07. These could be arranged in one tower 30 layers deep and also, in two strings of 10 wafers that will test the layer readout design. For the purpose of this budget, we assume only 10 wafers will be bump-bonded in 2006. The bump bonding effort over the two years includes supplies (photoresist, indium, miscellaneous): $2,000; Microfab Facility charges: $5,600; Ti/W sputtering target: $850. The microfabrication facility at UCD charges $28/hr with a maximum of $2,800/month once the usage exceeds 100 hours. We estimate 1 day/chip for patterning, for a total of 30 days, which can not be accomplished in one month. Hence, we have budgeted for a total of 2 months of usage of the microfab facility.

The NRE estimate for the flex cable is $2,800, based on actual quotes obtained from a vendor based on a preliminary design that contained all the required features but not the ultimate complexity of the design. We anticipate two rounds of prototyping in order to produce the final version of the flex cable. The actual fabrication cost is estimated at 1.0k$. We envision two rounds of design and fabrication, giving a total of about 8k$.

The indirect rate is 26%.

UC Davis two-year budget, in then-year k$:

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Combined Oregon and Davis totals, in then-year k$:

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References


6.6: Digital Hadron Calorimetry for the Linear Collider using GEM based Technology

(renewal)

Calorimetry

Contact person
Andy White
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Institution(s)
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Funds awarded (DOE)
FY04 award: 70,000
FY05 award: 35,500

New funds requested
FY06 request: 177,490
FY07 request: 176,041
Digital Hadron Calorimetry for the Linear Collider using GEM based Technology
University of Texas at Arlington, University of Washington

Personnel and Institutions requesting funding
Andrew Brandt, Kaushik De, Jia Li, Mark Sosebee, Andy White*, Jae Yu*, Tianchi Zhao
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Project Overview
The goal of this project is to develop the implementation of digital hadron calorimetry for future Linear Collider detectors using Gas Electron Multiplier technology [1]. This is a critical and essential development for future experiments that will rely on the Particle Flow Algorithm (PFA) approach to achieve the required jet energy and jet-jet mass resolution. Figs. 1 and 2 show schematics of this approach.

![Fig.1 Schematic of double-GEM detector]

The ionization signal from charged tracks passing through the drift section of the active layer is amplified using two-stage GEM foils. The amplified charge is collected at the anode, or readout pad layer, which is at ground potential. This layer is subdivided into the small (~1cm x 1cm) pads needed to implement the digital approach. The potential differences required to guide the ionization are produced by a resistor network with successive connections to the cathode, both sides of each GEM foil, and the anode layer. The pad signals are amplified, discriminated, and a digital output produced. The GEM design allows a high degree of flexibility with, for instance, possibilities for microstrips for precision tracking layer(s), variable pad sizes, and optional,
Status Report
In order to be able to design a hadron calorimeter system based on GEM technology, we need to establish the basic characteristics (signal sizes, efficiency, hit multiplicity, magnitude and frequency of crosstalk, rate capability) of GEM chambers with small anode pads, to develop the capability to make large area GEM foils, and to be able to reliably simulate the behavior of our prototypes. We constructed and learned how to reliably operate small GEM chambers, and obtain some initial results. In FY05 we made a number of essential measurements with our small chambers, have obtained and characterized our first large-area GEM foils, and have produced a first round of simulation results. This work is described in the following sections.

Results from GEM prototypes
We have continued to make measurements using our small GEM prototype. A view of a prototype is shown in Fig.3. The 3 x 3 array of 1cm$^2$ anode pads is shown in Fig.4. Signal amplification is achieved using QPA02 chips from Fermilab (originally developed for readout of a silicon-based detector). We initially used an Ar/CO2 70:30 gas mixture and obtained gain values close to those measured by the GDD group at CERN [1]. However, we have recently changed to an 80:20 mixture, which yields signals about three times larger for the same potential across the foils and has not caused any deterioration in chamber performance or stability.

Efficiency measurement
To measure the efficiency of our prototype we used cosmic rays at essentially normal incidence. In order to guarantee that a track passed through the central region of the anode array (the central pad or the inner part of one of the surrounding pads), we had to move the top trigger counter out to about 1m away. This, of course, meant a low rate for accumulating data. The physical separation of the anode pads is 250µm. However, this gap should not lead to a loss of efficiency as the field lines, and hence the electrons, all end on one of the copper pads. With a 40mV threshold (compared with a typical average signal size of 200mV after amplification) we obtain an efficiency of 94.6% after trigger counters were arranged to guarantee hitting the pads - see Fig. 5. As discussed below, this is in good agreement with the expectations from our simulations.
Hit multiplicity measurement

To measure the hit multiplicity on our 3 x 3 pad array, we used a Sr-90 source, collimated so that the decay electrons hit the central pad region only as shown in Fig.6. A cosmic ray veto also covered the complete area of the pad array. The thresholds on all nine channels were set to the 40mV value that gave the 94.6% efficiency described above. The hit multiplicity is the ratio of the number of hits in all nine pads to the number of hits on the central pad. We obtained a value of 1.27, giving the GEM technology an advantage over, for example, RPC’s for which a hit multiplicity in the range 1.6 – 1.7 has been measured [9].

Development of large-area GEM foils

In FY05 we have worked with 3M Corporation to specify, produce, and test 30cm x 30cm foils. This was a precursor to producing the 1m x 30cm foils needed for a GEM-DHCAL test beam module. The 30cm x 30cm size was mainly dictated by the available etch window of the 3M reel-to-reel flex circuit production process. The Electronics Solutions Division of 3M that we have been working with had previously made circular GEM foils of various sizes for colleagues at Purdue University for TPC studies. Over a period of a month we evolved a detailed design, finally resulting in the production of a roll of 80 30cm x 30cm foils, each with 12 high voltage segments. A view of one of the first foils is shown in Fig. 7, and a high magnification view of a section of foil is shown in Fig. 8. We experienced some initial problems with the delivery of the foils: due to an unfortunate choice of plastic film separators between the foils, a large area of surface staining was present on each of the initial 30 foils. 3M took back these foils and have recently delivered another 30 foils with clean surfaces.

As a service to some of our colleagues, we are also supplying at cost a number of foils to U.Victoria (for tracking studies), Louisiana Tech. U. (also for tracking studies), U.Washington (a collaborator on this proposal), and Changwon National U. and Tsinghua U. (for general GEM studies).

We have made initial measurements of the currents drawn when various potential differences were applied across each high voltage sector on each foil. We established a procedure to be followed by our undergraduate students testing the foils. We defined a foil to be acceptable if it passed visual inspection, and if all HV sectors drew a current less the 10nA after 30 seconds.
Possible alternative approach to standard GEM foils

We have been considering a potentially interesting alternative to the standard GEM foil technology. Recent work [2] has shown that a so-called “thick-GEM” (THGEM) can, in a single layer, achieve multiplication levels typical of at least a double-GEM device. A THGEM is essentially a circuit board, clad with copper on both sides through which holes have been drilled. A typical configuration might be a 0.4 mm thick board with 0.3 mm diameter holes spaced 1 mm apart. An example [2] is shown in Fig. 9 and gain results in Fig. 10.

Since in our application we use rather large pads (compared say with a microstrip tracker) the sparser array of holes should not be an issue. Use of this approach could save about 0.5 mm in radial space per layer of the hadron calorimeter, or 2 cm overall for 40 layers. With the detector costs scaling as +$12M/mm increase of the superconducting coil radius, this could be a significant cost saving.

THGEM’s can potentially be made using a laser drilling technology, although this may limit the hole diameters to about 0.2 mm. Smaller holes can be drilled at the rate of about 18,000/minute. In order to allow the safe use of high potentials across the THGEM’s, avoiding discharges, it is desirable to etch away some copper from around each hole after drilling. This can be achieved by
the use of standard etching techniques, with care being taken to co-center the drilled and etched holes.

An interesting possibility for the hadron calorimeter is to shape the THGEM boards to provide a true cylindrical geometry. This may have certain advantages in reducing the problems associated with calibration and the setting of discrimination levels for the digital calorimeter since more radial tracks would cross the active gaps at close to normal incidence.

We therefore propose to evaluate this alternative approach. We have received some small THGEM samples from colleagues at the Weizman Institute. We will also have our own THGEM made locally and compare their characteristics and cost of fabrication with standard GEM foils.

Assembly of large area GEM detectors

We will assemble five 30cm x 30cm double-GEM chambers. The first step is to mount the GEM foils on frames. The frames, made of FR4, were designed at UTA following an initial design by Dean Karlen, U.Victoria. They were made for us at Lab 8, Fermilab on their Thermwood machine and kindly paid for by our ILC colleagues at Fermilab. The design of the 1 mm frame is shown in Fig. 11. The foils will be stretched, then mounted, on the frames using the transfer jig shown in Fig. 12. A schematic of the layer assembly for the chambers is shown in Fig. 13.

![Fig.11 Frame for 30cm x 30cm foils](image1)

![Fig.12 Transfer jig for framing foils](image2)

The anode boards will have the usual 1cm x 1cm segmentation, with readout traces taken from plated-through holes on the reverse side to the edges of the boards, as shown in Fig. 14. This arrangement, together with three preamp boards per detector will allow us to read out an 8 x 8 array of anode pads per chamber.

![Fig.13 30cm x 30cm chamber assembly](image3)

![Fig.14 Anode board for 30cm x 30cm](image4)
Readout of the Large Area GEM Chambers

For our 10cm x 10cm prototypes we have used a 32-channel board based on the QPA02 chip, originally designed at Fermilab for silicon detector readout. Fermilab PPD has kindly handled the production of twenty more of these boards for us – sufficient for 96 channels for each of the 30cm x 30cm chambers, plus spares. We have developed and made adapter boards to allow the plane of the readout boards to be parallel to the plane of the chambers, in turn allowing the five chambers to be stacked close together if needed.

The University of Washington group has worked on the DAQ system planning for the GEM chamber cosmic ray test stack. The role of the DAQ system is to receive output signals from preamplifier cards based on the Fermilab QPA02 ASICs that amplifies the signals collected on the pads of the GEM chambers, discriminate the signals and send the digitized signals to a computer. Given the limited funding for this project, modifying and reusing an existing system was considered. For this, we have investigated two possible solutions. The first solution is to reuse the MWPC front end cards that the UW group built for a Fermilab experiment in the late 1980s. If we reuse these cards, modules for data control and interfacing with the computer will be needed. The second solution involves using DAQ cards built for the muon system of the BESIII detector in Beijing. The IHEP in Beijing has agreed to supply enough cards for our cosmic ray test at a minimum or no cost. We have been in contact with them and expect to receive these cards in January 2006. We will need to do some tests to determine which solution is best suited for the GEM cosmic ray stack test.

The IHEP DAQ system consists of two parts: front end cards (FECs), see Fig. 15, and control modules (NIM format). Each FEC has 16 discriminators with software selectable thresholds. Each card has a FPGA that receive and store the data locally. A maximum of 16 cards can be daisy chained and the data stored in these cards can be sent to the control module in serial. The control card has a USB port. A DAQ sequence is initiated by an external trigger and the data from the control module is sent to the computer via a USB cable.

![Fig.15 The layout of the FEC card](image)

Our GEM cosmic ray stack will have 480 channels that require 30 FECs and 2 control modules. The FECs are designed to be mounted on the edges of detectors. We will need to design mounting frames for these cards. Cables and power supplies are also needed. The DAQ software is written based on Delphi and Windriver development platforms. We may need them to modify the DAQ software to meet our needs.

Simulation Studies

The UTA group has successfully implemented a double GEM layer geometry into the existing Mokka [3], a GEANT 4 [4] based simulation package, replacing the scintillation counter...
sensitive layers in the TESLA TDR hadronic geometry (stainless steel/ scintillation counter) with the double GEM layer structure. We retained all other detector structure the same as in TESLA TDR detector design [5]. In order to optimize computer CPU resources, we have implemented a simplified version of the GEM instead of detailed geometry introducing a new composite material, GEM. A comparison using single 75 GeV pion events shows virtually identical energy deposit in half the CPU time for the simplified mixture version compared to a detailed geometry of a double GEM structure. Based on this study, we have decided to use the simplified geometry for further studies.

Using the established simulation and analysis software, we have completed the study of double GEM based calorimeter performances in analog and digital readout modes with a realistic threshold value at 98% of a MIP, using single pion samples whose energies range from 5 GeV to 100 GeV. The intrinsic gain of the double GEM sensitive layers was chosen to be 3000, the value measured from our prototype, which is within 15% of other measurements. The results from these studies have been compared to TESLA TDR detector performance studies based on Mokka. The resolution obtained from our studies of TESLA TDR detector is consistent with results from other studies, if an energy-independent EM and Hadronic relative normalization factor of 0.65 is used.

We used the same data set generated for the analog studies of GEM calorimeter to perform digital studies. Fig.16.a shows a profile plot of E vs N for hit-to-energy-deposit conversion.

Figure 16. (a) A profile plot of energy deposit vs number of cells hit used for hit-to-energy conversion. (b) A scatter plot of energy deposit. A saturation at the higher energy deposit is apparent.

Fig.16.b shows the scatter plot of energy vs number of hits, which demonstrates the linearity of the detector in its digital readout mode. As expected saturation in the number of cells hit begins to appear at the higher energy deposits due to larger energy densities in a cell. It has been observed in our study that 85% of the cells are hit once for 5 GeV single pion showers while this fraction decreases to 74% for 100 GeV single pion showers. A study of number of hit cell vs layer number for 50 GeV pion shows that it directly mimics the energy deposit distribution along the layer, providing direct evidence and confidence that a GEM based calorimeter can be used as a digital calorimeter properly representing energy deposit of showers. We used the number of hit
cells versus energy deposit to extract the hit-to-energy-deposit conversion factor for digital readout mode analysis.

![Graphs showing energy deposit distributions](image)

**Figure 17.** Energy deposit of 50 GeV pions (red circles) in GEM DHCAL (a) in analog and (b) in digital modes. (c) Energy deposition of a 50 GeV muon (red histogram) and the cut efficiencies as a function of discriminator threshold (dark red).

More sophisticated procedure for fitting the responses from EM and Hadronic components had to be developed to accommodate the changes in energy deposit distributions for analog and digital modes. The energy deposit measured in analog mode shows a remaining large tail due to Landau fluctuations. These large fluctuations are suppressed in digital mode since the tail on higher energy deposit within a cell is still counted as one hit forcing the distribution Gaussian. Figs. 17.a and b show distributions of energy deposit by 50 GeV pions for analog and digital modes, respectively.

Fig. 17.c shows the energy deposit of a 50 GeV muon in the GEM calorimeter (red histogram) and the MIP efficiency as a function of discriminator threshold (dark red). The arrows indicate the threshold and the corresponding efficiency. From this study we find that 0.23 MeV for muon energy deposit gives 95% MIP efficiency. The performance of GEM DHCAL with thresholds has been completed without incorporating realistic noise measurements. The above studies of GEM DHCAL performance were carried out by two Master's students. The results from the data analysis have been documented in S. Habib’s [6] and V. Kaushik’s Master's theses [7].

Performance studies show that GEM calorimeter responses for analog and digital are very closed to each other as we expected. Fig. 18.a shows single pion energy resolutions for GEM DHCAL (green) which is comparable to the TESLA TDR [5] detector (red) except at low energy. The single pion energy resolution of the GEM digital calorimeter is comparable to that of TESLA TDR and other detector studies (black triangles) for most the energy ranges except at low energies. This is reflected in the resolution function as the digital mode showing larger sampling terms (~70%) with relatively smaller constant term. On the other hand, the GEM analog mode resolution is significantly worse than other detectors or than the digital modes. This behavior is caused by the large remaining Landau fluctuation in energy deposit as discussed above. Figure 18.b compares the jet energy resolution for GEM DHCAL using a “perfect” PFA (blue), which has a sampling term of 30%/√E, to other detector technologies, using the single pion energy resolution obtained for GEM DHCAL. This study clearly demonstrates the potential of PFA with
GEM DHCAL to achieve the excellent jet energy resolution required by the physics program at the ILC.

In order to make the transition to the next level of simulation, it was necessary for us to convert the simulation package into a version that would produce output in LCIO format, commonly used in the ILC community. We have therefore been working on implementing an upgraded Mokka simulation package. The energy resolution with this new package shows a slight improvement in its sampling term compared to previous studies, expected from recent GEANT4 changes. We have also been working with N. Graf and others on the SiD concept to implement GEM into the latest SiD geometry to carry out PFA development. We have requested samples of single and double pion events and single electron events from SLAC for this work.

FY2006 Project Activities and Deliverables

Completion of the 30cm x 30cm GEM chambers
We have taken delivery of the new 3M large GEM foils and must first finish testing them prior to use in chamber assembly. These tests should be completed in 2-3 weeks. We also hope to have similar test results from our colleagues sharing the foils at other institutions. Assuming that most of the foils check out satisfactorily, we will mount ten of them on to frames. We have also just received the anode printed-circuit boards for the new chambers. Following some more tests of assembly procedures, we will build five double-GEM chambers. This will take about two months to complete.

Testing of individual chambers
Prior to setting up a stack of five chambers we will characterize individual chambers. We will assess our ability to make chambers with a common performance in terms of uniformity of gain, efficiency, and hit multiplicity across their active areas. These tests will use both radioactive source(s) and cosmic rays, following our earlier tests on 10cm x 10cm prototypes.

Cosmic ray tests with five chamber stack
As a precursor to finding tracks in a calorimeter stack, we will arrange the five 30cm x 30cm chambers in a vertical stack for use with cosmic rays. The stack will be used to examine and produce results on the following items:
- Single cosmic tracks hit patterns.
- Hit multiplicity (vs. simulation)
- Signal sharing between pads (e.g., vs. angle)
- Efficiencies of single double-GEM counters
- Effects of layer separators
- Operational experience with ~500 channel system
- Possible test-bed for ASIC’s when available – rebuild one or more DGEM chamber

We expect to spend several months on these tests and their interpretation in mid-2006.

**Possible beam tests with 5 chamber stack**
We have the possibility of testing the five chamber stack (maybe starting with a single chamber) at the Fermilab MTBF (Meson Test Beam Facility). This would extend the tests with cosmic rays and give us valuable experience with MTBF for the planned full 1m³ GEM calorimeter stack. There is also the possibility of taking up an offer from our Korean collaborators of using a low energy electron test beam in Korea. The choice of facility and timing of these tests will be decided by practical considerations of schedule and availability in 2006.

**Development of GEM foils**
For the assembly of 1m² planes of GEM active calorimeter layers, we need 1m x ~30cm strips of GEM foils. Three such strips (doubled for DGEM chambers), each 30-33cm wide will then form an active layer of 1m². We have already discussed the need for these long foils with 3M and, in principle, there is no great barrier to adapting their reel-to-reel production line to make them. We will pursue this in 2006 and address issues of registration and tolerance down the long strips. The goal is to have the first long strips available for prototype large chamber assembly in the second half of 2006.

**Investigation of THGEM’s**
We will first use the small THGEM samples from Weizmann to build small chamber(s) and reproduce the Weizmann results for our own education. In parallel we will investigate the production of THGEM boards using PCB manufacturers in the local Dallas–Fort Worth area. If a manufacturer(s) can be found that can make larger pieces of THGEM at a lower or competitive cost with the 3M foils, we will proceed to make larger chambers and evolve a DHCAL design based on this alternative technology.

**GEM chambers in 5T field simulation study**
We have created a simulation of a GEM foil in MAXWELL and verified the electric fields and the number of holes needed to avoid edge effects. The next step is to include the magnetic field and then use GARFIELD [8] to study the modifications to the trajectories of drifting electrons in the combined field vs. the electric field alone. We anticipate that this could lead to a shift in the center of the ionization collected at the anode pads. We will also search for indications of spiraling electrons around the magnetic field lines which could cause unwanted large signals.

**Further PFA development**
We will work on PFA development as part of the SLAC/Argonne effort within SiD. We will take on one or more Master’s student(s) to do the code development for the GEM-based version of
the HCal. We will deliver performance study results for the complete SiD detector simulation with digital GEM-based DHCAL. This work will also extend into 2007 and beyond as refinements are made and further algorithm enhancements are made as we confront and solve problems such as cluster identification and track assignment, and neutral energy measurement. We are particularly interested in the issues related to the use of GEM active layers: the effects of low vs. high hit multiplicity, magnetic field causing offsets in charge deposition, digital threshold setting and relative (to scintillator) neutron insensitivity.

Test beam stack simulation development
We expect to participate in a testbeam experiment on the 2007 – 2008 time scale, contingent upon availability of funds. The geometry for testbeam experiment must be implemented and the corresponding software for reconstruction and analysis must be developed ahead of the actual data taking. Currently, Northern Illinois University has developed a testbeam simulation package. We plan to exploit the existing package and implement our GEM geometry into the system for the initial studies in the testbeam stack. Studies will also have to be conducted to determine particle types, energy range and statistics for adequate precision for the testbeam needs.

Develop trigger and timing system for Fermilab MTBF test beam
As part of the plan to use the Fermilab MTBF for ILC calorimeter studies, UTA has agreed to work on the trigger and timing system. We will investigate the current trigger counters and available signals in relation to the readout needs of the various CALICE and SiD modules proposed for exposure at MTBF. There are issues of asynchronous running at MTBF vs. the synchronous environment at the ILC. If we expose our 30cm x 30cm chambers to the beam at MTBF, as described above, this will no doubt give us valuable input for trigger and timing modifications for future running.

FY2007 Project Activities and Deliverables

Assembly and testing of large (1m x 30cm) GEM planes
We have made initial tests of the assembly procedure for the 1m x ~30cm planes. Fig.19 shows the result of one of these tests. We will further develop, and possibly semi-automate, this procedure in 2006 with the goal of completion at the time of the availability of the 1m x ~30cm foils from 3M discussed above. In 2007 we will assemble sufficient 1m x ~30cm planes to be confident in the procedure before beginning the work on the 1m³ stack.

Fig.19 Mechanical test of large GEM layer assembly
Start construction of 1m$^3$ test beam stack – conditional on funding

The principal task for the next three years (extending the scope of the current proposal) will be the construction and testing of a full size (1m$^3$) GEM-based digital hadron calorimeter stack. This is an essential step in the development of linear collider detector technology, in order to (a) demonstrate the viability of this technique (in parallel with the scintillator and RPC-based approaches), and (b) make critical, energy density measurements with fine spatial resolution (~1cm), to tune GEANT4 as a reliable tool for PFA development. The testbeam stack will be built at UTA using the 1m x ~30cm GEM foils. There will thus be 3 double-GEM panels for each of the 40 layers.

The 1m$^3$ beam test module, if fully instrumented, requires approximately 400,000 readout channels assuming 1cm × 1cm readout pads. The Fermilab PPD electronics group is developing a 64 channel ASIC that has an adjustable amplifier gain and can be used to readout both RPCs and GEM detector planes. This ASIC will receive signals from readout pads, discriminate signals, tag hits in time to facilitate shower reconstruction. It also has a serial I/O control, serial data output line and a trigger output as shown in the block diagram below. Each ASIC can readout a 8x8 detector pad array. We currently envisage an arrangement that we will have 6 large multilayer printed circuit boards to readout a 1m$^2$ detector plane. Each board will host 24 front-end ASIC chips, as shown in Fig.20.

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**Fig.20 Components of ASIC-based readout system**
Evaluation of the ASIC design has been started at Fermilab and Argonne. We will develop a front-end readout board design for the 30 cm x 30 cm double GEM chambers that we will construct in FY2006. This board requires 16 ASICs. When the GEM foil of final size (32 cm x 96 cm) becomes available in FY2006, we will extend the board size to 48 cm x 32 cm and design a readout system for the 1 m x 1 m plane of the 1 m³ beam test module. We expect that the design of these front-end readout boards will be somewhat different for GEM and RPC in terms of some mechanical aspects. The work for prototype ASIC chip testing and the front-end readout board development work will be shared between UTA and UW. We will coordinate our effort for developing front-end boards for GEM with the RPC group at Argonne.

For the beam test module, the output signals from the front-end boards will first be processed by the data concentrator boards and then sent to VME cards. These stages of the readout system will be identical for both GEM and RPC. Funding for this large-scale test is being sought from other sources.

**Develop design of hadron calorimeter for SiD based on GEM-DHCAL**

As UTA has been working with the SiD detector concept, in 2007, we will complete an initial design study for a full GEM-DHCAL system for SiD. We will address issues such as the minimization of chamber boundaries (dead areas), minimization of active layer thickness, mechanics and FEA of a GEM-based stack, absorber choice, total depth of the ECal+HCal system, digital readout signal routing at the module level, HV and LV supplies, and the gas system.

**Budget Justification: University of Texas at Arlington**

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This budget includes:
- 0.5 Postdoctoral Associate for each year – Dr. Jia Li who has done all the detailed design work on this project and has been responsible for building and testing the prototypes.
- A graduate student for each year to work on both the component and prototype testing and the development of simulation code.
- The fringe rate for the postdoc is 30% and for the graduate student it is 45%.
- Equipment funds, split over the two years, to allow the assembly of a cosmic ray test stand for the 5 chamber stack, and the development of full size active layers.
- Travel to allow participation in LCWS conferences, CALICE and SiD meetings and work on the test beam at Fermilab.
- Materials and supplies for the purchase of an initially small number of long GEM foil strips and other materials necessary to assemble the prototypes described here.
- UTA indirect costs are at a rate of 48%.

### Budget Justification: University of Washington

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This budget includes:
- Two months engineer salary to work on the readout/DAQ system.
- Fringe at a 30% rate.
- UW off-campus indirect cost at 26% rate.
- Travel to UTA, 2 weeks each time working on cosmic ray testing.
- Materials, software and supply for DAQ system.

### References


9. See e.g. talks by Lei Xia at LCWS05 or Snowmass ILC Workshop 2005.
6.9: Development of Particle-Flow Algorithms and Simulation Software for the ILC Detector(s)

(renewal)

Calorimetry

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(630) 840-8569

Institution(s)
Argonne
Fermilab
Iowa
Northern Illinois
Oregon
SLAC
Kansas

Funds awarded (DOE)
FY04 award: 35,000
FY05 award: 44,500

New funds requested
FY06 request: 66,840
FY07 request: 68,850
STATUS REPORT

Project Name
Development of Particle-Flow Algorithms and Simulation Software for ILC Detector(s)

Personnel and Institution(s) requesting funding
Northern Illinois Center for Accelerator and Detector Development, Northern Illinois University [1]

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C. Milstene et al., Fermi National Accelerator Laboratory,
R. Frey et al., University of Oregon,
G. Wilson et al., University of Kansas,
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Project Overview
The Northern Illinois University(NIU)/Northern Illinois Center for Accelerator and Detector Development (NICADD) group is interested in calorimeter R&D for the proposed ILC [1]. We are developing, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet reconstruction using particle-flow algorithms (a.k.a. “energy-flow algorithms”). Simulation/algorithm development and hardware prototyping are envisaged as the two main components of our efforts. This project addresses the first component while the second is the subject of a separate project.

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 fully realize the potential anticipated from a machine of this type, the detector components must be optimized, sometimes in unprecedented ways, taking full advantage of the most recent developments in technology. One such example is the hadron calorimeter which will play a key role in measuring jets from decays of heavy particles such as vector bosons, 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 requires dijet mass measurement within $\sim 3$ GeV, or, in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ ($E$ in GeV). Such precision in jet energy measurement, without a kinematically overconstrained event topology, is beyond any collider calorimeter to date. Similar precision in measurements of jet and missing momentum will be crucial for discovery and characterization of several other new physics processes as well as for precision tests of the Standard Model. Such ambitious objectives place strong demands on the performance of the calorimeters working in conjunction with the tracking system at the ILC, and requires development of new algorithms and technology.

The most promising means to achieving such unprecedented jet energy resolutions is through particle-flow algorithms (PFA). A PFA attempts to separately identify in a jet its charged, electromagnetic, and neutral hadron components, in order to use the best means to measure each. On average, neutral hadrons carry only $\sim 11\%$ of a jet’s total energy, which can only be measured with the relatively poor resolution of the HCal ($\sigma(E) \approx 0.6\sqrt{E}$). The tracker is used to measure with much better precision the charged components ($\sim 64\%$ of jet energy), and the electromagnetic calorimeter (ECal) to measure the photons with $\sigma(E) \approx 0.15\sqrt{E}$ ($\sim 24\%$ of jet energy). On average, only a small fraction of a jet’s energy is carried by particles with momenta greater than 20 GeV. Momentum measurements by the tracker are at least two orders (one order) of magnitude more precise than those from the calorimeter for particles below 20 GeV (100 GeV). If all particles in a jet could be identified correctly and all the energy could be associated perfectly, then a net jet energy resolution of $\sigma(E) \approx 0.18\sqrt{E}$ would be possible. Such perfection cannot be attained in reality, but $\sigma(E) \approx 0.3\sqrt{E}$ is still deemed achievable. However, this will certainly require extensive and simultaneous optimization of detector design and tuning of algorithm parameters.

A calorimeter designed for PFAs must be finely segmented both transversely and longitudinally for 3-d shower reconstruction, separation of neutral and charged clusters, and association of the charged clusters to corresponding tracks. This requires realistic simulations of

1. parton shower evolution,
2. particle interactions in the detector volume, and
3. sensor response to energies deposited in the sensitive media.

Accurate simulation relies heavily on analysis of data from beam test of prototype modules. The detector optimization requires the simulation, visualization, and analysis packages to be highly flexible, which calls for careful design and implementation of the software itself. For the first time in the history of particle collider experiments, detector design and algorithms will evolve in a bootstrap process through iterative feedback to each other.

Very large numbers of events will have to be simulated to evaluate competing detector designs vis-a-vis ILC physics goals. Characterization of signatures arising from processes predicted by some extensions of the SM will require simultaneous coverage of broad ranges of undetermined parameters. Parametrized fast simulation programs will thus have to be developed once the algorithms have stabilized. Parametrization of PFAs will require much work, and is one of our key objectives.
Status Report

Members of NIU, ANL, SLAC, and UTA began collaborating on PFAs, simulations, and software development efforts in January, 2002. Fermilab and universities of Kansas and Iowa have since joined the effort, and links have been established with European colleagues who had been active in this area already. The results that emerged have been presented at the Calor conferences, ECFA and ACFA meetings, the American LC workshops, and at the International LC Physics and Detector Workshops.

1. Detector optimization: Toward the optimization of the HCal design, the NIU team has pioneered investigations of energy estimators based on local hit densities as alternatives to the traditional way of simply dividing the energy measured by each cell by a fixed sampling fraction to estimate its energy. The former can be used quite effectively with the so-called “digital” calorimetry, where each cell offers only a binary (1-bit) output indicating whether or not it has received at least the energy expected from a minimum ionizing particle (MIP), as foreseen for the gas-based HCal designs (RPC, GEM). But it also helps extract more precise information out of multi-bit read-out of each cell, which remains an attractive option for scintillator-based designs.

We have been studying the performance of such estimators as functions of different weighting schemes, active media, dynamic ranges of the cell energy measurement, cell size etc. Our preliminary findings suggest that with sufficiently small cells, the density-based method yields a more precise measurement of the hadron energy, i.e., fluctuations in hit (or energy) density are smaller than those in the sampled energy of a hadronic shower. Use of local hit/energy density in lieu of the deposited energy to weigh the calorimeter hits results in superior energy resolution and separation of nearby showers. Through extensive simulation and analysis, we have gained some sense of the optimal cell sizes and geometry for best charged/neutral hadron shower separation in jets within the context of some specific overall detector parameters, but we continue to work on making the simulations more realistic and improve the credibility of these results.

We will now briefly summarize our HCal optimization and algorithm development efforts. The HCal must be optimized to achieve, with due consideration of costs, benefits, and risks, the best balance between the reconstruction and energy resolution of neutral-hadron-initiated clusters in a jet, and the ability to separate them from the charged components. This is intimately related to the first step in the development of a particle-flow algorithm as described below. The elements are highly inter-related, and must be optimized simultaneously. All figures in this section were generated using GEANT4-based detector simulation programs and reconstruction algorithms developed at NIU.

HCal absorber/active media properties: The reconstruction and analysis of physics events within the Java Analysis Studio (JAS)-based software environment developed at SLAC, is flexible in the choice of absorber and active media type and thickness within the limits of the HCal volume. Our group developed a GEANT4-based detector simulation package called LCDG4 that is fully compatible with this environment, and produced many data sets spanning a range of cell sizes and event types (sin-
gle particles as well as benchmark physics processes). LCDG4 served as the official standard for all mainstream algorithm development activities in America for 2+ years until the 2005 Snowmass workshop, when it was succeeded by a more sophisticated package called SLIC.\textsuperscript{1} Teams from NIU, ANL, SLAC, and Iowa, studied a wide variety of events simulated with LCDG4, which resulted in a set of algorithms that can be combined in a number of alternative ways in a full chain for jet reconstruction. We have been optimizing the HCals by comparing scintillator- vs. gas-based devices (e.g. RPC, GEM) as active media. Comparisons between dense materials (e.g. W) to less dense ones (e.g. Stainless Steel) as absorbers, are underway. Single-particle and jet energy resolutions will be used as performance measures. Substantial progress has been made in this direction already. The left panel of Fig. 1 shows the energy resolution as a function of single $\pi^\pm$ energy, estimated using hit density weighting, for two different lateral segmentations of the scintillator option, and the proposed segmentation for a realistic RPC design. The right panel of Fig. 1 shows the density-weighted angular widths of single-hadron showers as functions of their momenta in reasonably realistic scintillator- and gas-based designs. The more realistic gas-based geometry and the scintillator design under consideration give comparable results.

![Figure 1: Comparisons of scintillator vs. gas as the HCal active medium. Left: the fractional energy resolution of single $\pi^\pm$ using density-weighted clustering in scintillator and gas-based geometries. Scintillator tiles of 1 cm$^2$ (stars) is not a practical proposition, but it is studied to understand the dependence of energy resolution on lateral segmentation of the active layer for a given choice of technology. Even the realistic 9 cm$^2$ scintillator option (circles) offers a somewhat better resolution than a 1 cm$^2$ gas configuration (squares) under this particular weighting scheme. The two are comparable at higher energies. Right: the density-weighted angular width of single $\pi^\pm$s showers as function of their momenta, in HCals with 9 cm$^2$ square scintillator tiles (circles) and those with 1 cm$^2$ square gas-based cells (triangles for “Geom1” and squares for “Geom2”). The “Geom2” configuration is fairly close to the RPC design currently under consideration.](image)

\textsuperscript{1}Jeremy McCormick, the primary developer of SLIC, is a former NIU graduate student who gained experience in GEANT4 while working with our group. He was on a joint NIU-SLAC appointment during the development of SLIC.
**HCal transverse granularity/Longitudinal segmentation:** We plan to optimize the 3-d granularity of cells for the most promising PFAs vis-a-vis the active medium technology (see the left panel of Fig. 1). The methods developed here are generalizable to different total detector concepts, namely, SiD (most compact, Si wafers for tracking and ECal), LDC (medium sized, TPC for tracking, Si wafers for ECal), and GLD (large, TPC for tracking, scintillator-based ECal). The basic performance measure here is the ability to separate showers initiated by charged and neutral hadrons - the key to any PFA. The limiting factor in the overall jet energy resolution is the confusion term arising from imperfect association due to finite granularity and misassignment. From the reconstruction algorithm’s point of view, it is this term that poses the biggest challenge.

**Analog vs. digital readout for the HCal:** The question of optimal 3-d granularity is intimately related to that of the dynamic range of the readout, which needs to be evaluated by comparing jet energy resolutions. At the extreme, “digital” readout means a single-bit “yes/no” decision on whether or not a minimum ionizing particle (MIP) has passed through a given cell. Since such digital measurements are less susceptible to Landau and path-length fluctuations than full (12-15 bit) analog measurements, hit counting has smaller spread than energies samples in the active medium. We have shown that with small cell sizes (< 10 cm^2), and for single hadrons below 20 GeV, the number of cells hit can be a more precise estimator of the particle’s total energy than the sampled energy is. Since the spatial spread of a shower increases in a less-than-linear proportion to its energy, the advantage gradually disappears at higher energies. We have shown that a slightly expanded dynamic range (two bits, instead of just one) allowing multiple thresholds to classify the hit status of a cell can be effectively used account for this non-linearity.

**2. Particle-flow algorithms:** For the first time in calorimeter development, it is necessary to take into account the reconstruction algorithms in designing the detector(s). How good the jet energy resolution will be depends ultimately on how well the PFA is formulated and tuned. As the first step of a PFA, in 2003-2004 we implemented an algorithm that produces clusters of calorimeter cells using local densities of hits as weights. In 2005, this has been supplemented by the “directed tree” algorithm, which uses local density gradient vectors for cluster reconstruction. In both cases, the user can choose the parameters such as thresholds, neighborhood definitions etc. The clusters serve as a quasi-geometry-independent set of objects for the subsequent steps.

The directed-tree algorithm is currently in a 2-stage “training” phase. Figure 3 shows an example of the result of the first stage of the purely calorimeter-based cluster reconstruction by the directed-tree algorithm. In the second stage, the Monte Carlo truth is consulted to check which of the clusters are “satellites” or “fragments” and to determine which main cluster a given fragment should be attached to.\(^2\)

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\(^2\)“Fragments” are small clusters that sometimes appear separated from a “main” cluster even though both originate from the same particle.
Figure 2: The fractional resolution of single $\pi^\pm$ energy using full analog (circles), 1-bit digital (squares), and 2-bit digital (triangles) read-outs. We find that 3 thresholds (i.e. 2-bits) is optimal.

We see in Fig. 3 that there are, as one would expect, very few fragments when the showers are well separated.

Information necessary to run the second stage will not be available in real data. It is used only as part of training, to optimize the parameters used in clustering and merging in the first stage. As the parameter-tuning improves in the first stage, its output should approach that of the second stage. An example performance of the two-stage process is shown in Fig. 4. While the parameters for the EM calorimeter seem to be reasonably well-tuned, those for the hadron calorimeter need further tuning (we have just implemented the algorithm, no work has yet been done on parameter optimization.)

The second step is to extrapolate the tracks and match them to clusters whenever appropriate, so that the energies of all charged-hadron-induced clusters can be replaced with the corresponding track momenta. The third step is to identify the photons by shower-shape analysis in the ECal. The final step involves combining the track momenta with photon and neutral hadron energies to produce high-precision jet energy measurements.

To facilitate portability of the algorithms across regional boundaries and detector design choices, we always try to minimize the dependence of implementations of the high-level algorithms on detector geometry details.
Figure 3: Cluster-finding by the “directed tree” algorithm. The left panel shows the end-view of a number of single hadrons hitting the calorimeter at the same polar but different azimuthal angles. The right panel shows how the directed-tree algorithm resolved the individual clusters.

In addition to the clustering algorithm from NIU and alternative ones from ANL and Iowa, we already have separate preliminary codes for identification of minimum-ionizing-particle track segments (NIU, Iowa), propagating the tracks through the calorimeter taking energy loss into account (FNAL, NIU), photon reconstruction (SLAC, Kansas), and reconstruction from these of PFA jets (ANL, NIU, Iowa). We are very close to combining these pieces into fully functional and completely honest jet-finding algorithms. The PFA developed at NIU, leads to full jet reconstruction by using Monte Carlo “truth” for track matching. A representative result of this is shown in Fig. 5 (this figure uses the older clustering algorithm - we are working on integrating the new algorithm into full jet reconstruction). We see that this PFA affords a 40% improvement in jet energy resolution compared to a traditional purely calorimetric measurement. For full PFA-based jet reconstruction, the current resolution on $M_Z$ is 3.9 GeV, 30% above the target of 3 GeV. We have some ideas on how it can be improved (see plans for out-years below), although how far they will take us remains to be seen.

3. Detector simulation: The NIU group has also made significant contributions to LC detector simulation software during the past 3 years. We ported and have been maintaining all of the current American software on the Linux platform. Since mid-2002, we have been processing simulation requests from several groups engaged in LC R&D, on Linux farms at NIU and Fermilab. We organized a workshop at NIU/NICADD in November, 2002, to bring the groups together, chart a plan, and set out in an organized manner. This was followed by similar workshops at SLAC in 2003, at ANL in 2004, and at U.
of Colorado, Boulder, in 2006. In FY2004 we produced, with groups across the world as signatories, a preliminary “requirements document” for the simulation software suite for the ILC detector(s) [3].

We have made substantial contribution to the following simulation software projects:

**Simulation of full detector concepts:** We developed, in close collaboration with our colleagues at SLAC, a stand-alone GEANT4-based simulation package called LCDG4. It supports run-time geometry specification, and fully complies with the model put forth by the ALCPG simulation group, and adds several useful functionalities to it [5]. It produces “raw” hit output in the globally accepted LCIO format and supports projective geometries in $\theta$, $\phi$, as well as non-projective ones with cells of constant linear dimensions. For over 2 years, LCDG4 was the official standard detector simulator for ALCPG. It has recently been succeeded by a newer, more versatile, package named “SLIC”.

**Simulation of test-beam prototype modules:** As members of the CALICE collaboration (CAlorimeter for the LInear Collider with Electrons [2]), and in active cooperation with our European colleagues, we produced a GEANT4-based simulator for the detector prototype module that is expected to be exposed to test beams over a period of 3-4 years starting in mid-2006. This program, called “TBMokka” is built on an alternative simulation framework called “Mokka”, developed independently by our European colleagues. Our involvement in the development of TBMokka gradually came to an end when the student who was working on it moved to SLAC to subsequently become the primary developer of SLIC.
Figure 5: The estimated jet energy normalized to the true energy in $e^+e^- \rightarrow ZZ \rightarrow 4j$ events at $\sqrt{s} = 500$ GeV events using purely calorimetric measurement (left) and the PFA developed at NIU (right). The calorimetric estimation uses traditional analog energy measurement, while the PFA uses semi-digital (2-bit) measurement in this case. The PFA can be used in analog mode as well. No kinematic fitting based on event topology is used in either measurement.

**Simulation of the signal extraction process following energy deposition:** In another major endeavor, we have designed and implemented the first version of a package, called “DigiSim”, to simulate the conversion of energy deposits in the active media (simulated by GEANT4) to electronic read-outs[7]. This package offers the user a simple, flexible, extensible, and standard way for parametric fast simulation of the effects of thresholds, noise, cross-talk, inefficiencies, attenuation, and timing, that are involved in signal collection, propagation, and conversion to persistable form (digitization). The process consists of reading the simulated energy deposits in cells, applying any user-defined transfer function, and finally writing out the digitized hits in the same “raw data” format as for real data. The transfer function can be encoded in one or more sequential “modifier”s. While most modifiers will operate on single cells, those that correlate multiple cells (e.g. cross-talk) are geometry-dependent. DigiSim reads the detector geometry and makes the neighborhood definition available to the user in a transparent way. As a result of inefficiencies, some cells that received energy deposits from a particle will not appear in the collection of digitized hits, while the opposite will happen due to cross-talk. DigiSim keeps a complete account of these mappings so as to allow the user to trace the effects of DigiSim and the performance of his/her algorithms. A supplemental ADC-to-GeV conversion step, which would correspond to applying the
calibration constants in real data, is supplied as well. This allows reconstruction and analysis codes written for “ideal” simulated hits (the GEANT4 output) to be run essentially unchanged on the post-digitization hits through an interface that is inherited from the older version without DigiSim. To estimate how the above-mentioned effects affect a given algorithm, one would then simply compare the results obtained using a realistic set of values for the detector effects to those obtained using an “identity” modifier. The identity modifier thus allows DigiSim to be permanently integrated into the simulation chain. A simplified class diagram of DigiSim is shown in Fig. 6, while Fig. 7 shows the scheme for transforming the list of GEANT4 energy deposits to digitized “raw hits”. Although so far we have only tested DigiSim for the calorimeter, it can be used for other subdetectors just as well. Applications to central tracking and muon system are anticipated in the near future.

3 Only minor modifications are needed to account for the fact that the mapping between the two sets may not be exactly one-to-one due to the detector inefficiencies and cross-talk, as explained in the text.

4 We have even received an enquiry for possible use of DigiSim in a particle astrophysics experiment.

Figure 6: A simplified class diagram of DigiSim. Full arrows represent inheritance. Hollow arrows represent containment (solid) or use (dashed) relationships. New modifiers can be added easily using the existing ones as examples. Only the part dealing with calorimeter hits is shown in this example.
Here are some of the salient features of DigiSim:

- DigiSim adheres to the LCIO event data model, which is now universally accepted by the ILC detector community. As a result, it can be used on all the different detector concepts - SiD, LDC, GLD, as well as test beam prototypes - even if the GEANT4 simulation is done by different programs, as is presently the case.\(^5\)
- DigiSim has been implemented in both Java and C++. The Java implementation is designed for use in the \texttt{org.lcsim} environment adopted in the Americas, while the C++ implementation works within the \texttt{Marlin} framework, which is the official standard in Europe.
- DigiSim reads all its parameters from intuitive ASCII "steering" files that are read at run time. Thus, the user does not have to recompile his/her reconstruction/analysis code to change a DigiSim parameter.
- The steering files have the same format in the Java and C++ implementations - a given steering file will produce the same effect in \texttt{org.lcsim} and in \texttt{Marlin}.
- DigiSim can be used either in a stand-alone mode to produce a persistent output, or as an on-the-fly preprocessor to the reconstruction program. In stand-alone mode, it produces output in the same format as that envisaged for the real data (except, of course, the simulation output also contains the "Monte Carlo truth", which the real data does not). Since DigiSim is fast compared to most pattern-recognition algorithms used in event reconstruction, the on-the-fly mode is suitable when one does not wish to write large intermediate output files on disk, e.g. when one is changing the DigiSim parameters from one run to another. The stand-alone mode may be the better choice when a stable set of parameters has been agreed upon for sharing between multiple users.

\(^5\)The official GEANT4-based simulation programs are: SLIC for SiD, Mokka for LDC, Jupiter for GLD, and TBMokka for the CALICE test beam prototype.
Figure 8: The effect of DigiSim on energy deposits by 10 GeV muons through a scintillator-based hadron calorimeter: (a) Scintillation light yield before (blue) and after (red) modeling of cross-talk, (b) After cross-talk simulation (magenta), effects of the geometric acceptance (green) and quantum efficiency (yellow) of the photodetector are simulated, (c) Effects of exponential (indigo) and Gaussian (red) noise and discriminator (magenta), (d) Comparison between the particle energy deposited in elements of the active medium (green) vs. “raw” hits as expected in real data (yellow). In all plots, both the abscissa and ordinate are shown in log scale.

An example of some of the effects simulated using DigiSim is shown in Fig. 8. Distribution functions of parameters such as efficiencies, cross-talk etc. may be expressed in either continuous (analytic) or discreet (histogram) form. Since particle-flow algorithms must deal with individual showers in a jet, they are expected to be more sensitive to systematic deviations at the single hit level than traditional jet-finding algorithms, where a single post-reconstruction scaling often suffices to bring Monte Carlo in satisfactory agreement with data. Therefore, any high claim to the performance of such an algorithm must be substantiated with a realistic accounting of the above-mentioned detector effects. Thus, DigiSim plays a vital role, and has been warmly welcomed by the user community worldwide. After a due certification process, the Java implementation has recently been released in a production version. The American ILC detector simulation group has ratified DigiSim as an integral part of its simulation chain. We hope that it will be adopted in Europe as well once some features still missing in the C++ implementation are incorporated.6 We expect DigiSim to be used extensively in the near future in the simulation of both the various test-beam prototypes and full-detector designs.

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6This is not entirely trivial since there are fundamental differences in the ways detector geometries are handled by the simulation/analysis frameworks in the Americas and in Europe.
To summarize, we have met all of the objectives for FY2005 put forth in our original proposal, namely completion of DigiSim and a first version of a class of particle-flow algorithms that can work with both analog and digital readouts. We have also continued to process detector simulation requests from the entire ILC community. All of our code is publicly available through the official repository of the ALCPG simulation and algorithms working group. Extensive documentation is available at our web site [1]. Additional information and interactive help are provided on request.

The steady progress that we have achieved so far has been made possible by funding received for this purpose during the past 4 fiscal years from DOE and NSF, in addition to generous, but less specific, funding from the Department of Education. In FY 2002 we received $45K from the DOE under its Advanced Detector Research program. An exploratory grant of $8.5K was awarded by the NSF in FY2003. In FY2004 and FY2005 we were awarded $35K and $44.5K, respectively, through LCDRD for our simulation software and algorithm development activities.

Activities outlined in this proposal are synergistic with the proposals for hardware prototyping of different technology choices. We will continue to remain in close contact with the groups involved in hardware development for the ECaI and the HCal.

**FY2006 Project Activities and Deliverables**

Experience gained during the past year have led to recognition of new issues and some rearrangement of priorities. In FY2006 we will integrate DigiSim into our reconstruction algorithms and study the effects of various detector imperfections on algorithm performance. Although DigiSim is ready for use, some improvements are planned in order to further enhance its flexibility, ability to keep track of history (e.g. in the stand-alone mode, to record in the output exactly what transformations have been applied), and error-reporting capabilities.

On the reconstruction algorithm development front, we will continue to improve pattern-recognition techniques, optimize the parameters of the algorithms, and compare simulations of different options for active medium technology, absorber material, and geometry (segmentation). In particular, we need to understand how the performance of an algorithm depends on the radial segmentation of the HCal vis-a-vis its thickness in terms of interaction lengths. It is extremely important to strike the right balance between the thickness and the number of layers since the geometric thickness of the calorimeter is severely constrained by considerations of the calorimeter and the magnet costs - so much so that the containment of hadronic showers is a matter of concern in the SiD design.

Also, there are several issues that need to be addressed to fully assess the limit of PFA performance:

- Much work is needed to minimize incorrect associations of “fragment” clusters: significant errors can result when a fragment originating from a neutral particle is incorrectly associated with a charged particle, or vice-versa.
- An important action item is to improve the propagation of charged particle tracks through the calorimeter using progressive fitting techniques that take into account the...
energy loss and possible scattering. We have started working on this with C. Milstene of Fermilab.

- The calorimeter designs currently on the table are not inherently compensating. Separate determination of response to electromagnetic and hadronic interactions in different sections of the calorimeter is high on our list of priorities. The dependence of these responses on the polar angle needs to be studied as well. Since all cells in a given section have fixed linear, rather than angular, dimensions, the difference may be significant.

- Another important issue is the differences in energy deposition patterns between different types of neutral hadrons, e.g. $n$, $\bar{n}$, and $K_L^0$. For a given kinetic energy, these particles will deposit different amounts of visible energies in the calorimeter. We need to investigate how much we may stand to gain by identifying those differences.

We expect to accumulate a substantial volume of test beam data by the end of FY2006. Careful analysis of those will be critical for tuning our simulation and reconstruction programs. A significant part of our efforts will have to be devoted to this.

Comprehensive studies of critical physics processes will have to be carried out in order to understand the impact of the calorimeter performance on the physics program of the Linear Collider. These studies will employ both the analog and digital versions of our PFAs. We plan to continue with further development of PFA-based jet-reconstruction and a partial assessment of physics reach vs calorimeter performance for the ILC.

Although we plan to start addressing most of the above issues during FY2006, considering the available resources, it is not realistic to expect to complete them all within the span of one year. We intend to report on tangible progress by the end of FY2006 and hope to come to reasonable conclusions on the key issues by the end of FY2007.

**FY2007 Project Activities and Deliverables**

In FY2007, we will try to complete the studies listed above. We will also complete the physics assessment with a clear statement on the desirability of a digital or analog option for the hadronic calorimeter. This will, of course, depend to a large extent on the test beam experience as well. If all goes well, we will also start the development of parameterized simulations of the particle-flow algorithms. The technology and geometry are expected to have been narrowed down by that time, thus setting the stage for such parametrized fast simulation for extensive physics studies. By the end of the third year we expect to produce, in collaboration with other groups, a fast simulation program based on PFAs. In addition, extensive benchmarking of critical physics processes, as well as evolution of pattern-recognition and reconstruction algorithms will continue.

**Budget justification:**

The above activities will be carried out by NICADD staff members. Specifically, one Research Scientist has been working full time on the proposed software R&D, and is expected to continue likewise through the next 2 years. We request that half of his salary be borne by the grant in question.
Communication of progress and exchange of ideas through international workshops and conferences will be crucial for our endeavor to have a global impact. Based on the FY2005 experience, we estimate five domestic and two international trips per year. A part of these travel expenses should be covered as well.

Fringe benefits to personnel at NIU’s mandated rate of 52% of salary, and indirect costs at the off-site rate of 26% (instead of the usual 45%, since the requested personnel will work in offices at Fermilab allocated specifically for ILC R&D) are included in the requested amount.

Two-year budget, in then-year K$

**Institution:** Northern Illinois University

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**References**


[5] [http://nicadd.niu.edu/lcdg4/](http://nicadd.niu.edu/lcdg4/),


[7] [http://nicadd.niu.edu/digisim/](http://nicadd.niu.edu/digisim/),
6.10: Investigation of ECAL Concepts Designed for Particle Flow

(renewal)

Calorimetry

Contact person
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Institution(s)
Kansas

FY05 award: 27000

New funds requested
FY06 request: 30,000
FY07 request: 30,000
STATUS REPORT

Investigation of ECAL Concepts Designed for Particle Flow

Personnel and Institution(s) requesting funding
Michael Ambroselli, Eric Benavidez, Carsten Hensel, Jonathan van Eenwyk, Matthew Treaster and Graham W. Wilson, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045

Collaborators
We have listed the names of various people with whom we have been in discussion with regarding participation in this and related projects.

Project Leader
Graham W. Wilson
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(785)-864-5231

Project Overview
The project goal is to investigate electromagnetic calorimeter (ECAL) design concepts suited to the linear collider physics program. The principal physics design criteria for the ECAL are i) hermeticity ii) the precise measurement of jet energies using particle flow and iii) a design suited to a general purpose experiment. All these criteria are closely tied to the overall detector design concept with the work undertaken being very relevant to assessing the relative merits of the SfD, LDC and GLD approaches, and therefore this project is being coordinated with the detector design studies.

In the following sections we outline some of the reasons for highlighting these criteria and discuss their impact on the ECAL concept.

[Hermeticity] For $e^+e^-$ center-of-mass energies beyond $m_Z$, physics processes with W's or Z's decaying in channels with 1 or 2 neutrinos occur frequently. Potential new physics such as supersymmetry leads to final states with characteristic missing transverse momentum. A principal detector goal is that events with significant missing transverse momentum should not be faked by Standard Model processes without neutrinos. It is of paramount concern that high transverse momentum particles, particularly photons, are detected with zero inefficiency. In the very forward region, (nearer the beam than the forward tracking), extremely efficient detection of electrons from two-photon processes is mandatory. It can also be necessary to detect muons and mips in such regions depending on the event topology.

The hermeticity requirements influence the ECAL design as follows: (i) need to avoid pointing cracks (ii) requirement to detect minimum ionizing particles (iii) elimination of “intruders” such as cosmics and halo muons (iv) reasonably uniform performance over the complete solid angle

[Particle Flow] In the particle flow method of jet energy measurement [1], the ECAL is used to measure the energy, polar angle and azimuth of photons in hadronic jets. A major requirement is to avoid double-counting of charged particles and photons in the visible energy measurement. This is most easily achieved by placing the ECAL at large radius.
The essential issue for the ECAL is measuring the 3-momenta of the photons over a dynamic range of between about 100 MeV and 500 GeV.

We have studied the intrinsic contribution to jet energy resolution arising from electromagnetic energy resolution [2] and we confirm that fractional energy resolution of \( \approx 10\%/\sqrt{E} \) is necessary in order to not appreciably degrade the potential jet energy resolution of \( 18\%/\sqrt{E} \). For a realistic particle flow algorithm in a detector where the overall jet energy resolution attains \( 30\%/\sqrt{E} \), we expect this resolution would be dominated by confusion issues, and one could consider relaxing the electromagnetic energy resolution requirement substantially (perhaps by a factor of two) if jet energy resolution was the only physics concern (it isn’t!).

The measurement of \( \tau \)-lepton decays places severe constraints on the separation of charged hadrons from photons from \( \pi^0 \) decay. Kinematic reconstruction of events containing \( \tau \)-leptons places rather stringent demands on the ECAL. (HCAL is relatively unimportant since neutrinos are absent and \( K^0_L \) are rare).

Another aspect of the calorimeter design which should not be overlooked is the detection and measurement of hadronic jets in the forward region where the charged particle tracking is likely to be compromised, specialized functions need to be accommodated (eg. Bhabha acolinearity measurement, luminosity measurement), and in general the environment is less conducive to full reconstruction (pile-up from \( \gamma \gamma \) events).

[Design suited to general purpose \( e^+e^- \) experiment] Detection and precision measurements of electrons and photons is an essential element of an \( e^+e^- \) experiment. The measurement of Bhabha’s and the \( e^+e^- \rightarrow \gamma \gamma \) process are part of the basic program and are expected to play an important role in the measurement of absolute luminosity and the differential luminosity spectrum. Photons from initial and final-state radiation are often crucial aspects to doing some of the physics. With the prevalence of “radiative-return” events and events from two-photon interactions, the tagging of the initial-state photon or a scattered electron can be essential to physics analyses. \( \ell \ell \gamma \) events will be a useful cross-check of the center-of-mass energy determination.

Given that we don’t know what new physics will be explored at the linear collider, there is little strong guidance on the required energy resolution for the ECAL. One scenario which deserves more investigation, as it is one of the more compelling constraints on the ECAL energy resolution, is the measurement of the Higgs branching ratio to \( \gamma \gamma \) presuming a Higgs mass of around 120 GeV. This was studied in [3]. The best measurement will come from the WW fusion channel \( (e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma) \) at the highest center-of-mass energy which has to compete against a large non-Higgs Standard Model background. This measurement would be complementary to LHC because together with other channels the BR could be measured directly. For similar reasons to LHC, the ECAL mass resolution directly influences the measurement precision. For this kind of application, the constant term in the energy resolution can be just as important as the stochastic term, and so an ECAL design which minimizes non-uniformities and can be easily calibrated is important.

**Detector Design Considerations relevant to ECAL**

The final detector designs will be heavily influenced by the choices made for the calorimetry. Some of the main design parameters which need to be considered are: the chosen B-field, the inner radius of the ECAL, the radius of the coil, and the aspect ratio (ie. the polar angle at which to change from a barrel to an endcap geometry).
Much of the current ECAL effort has been directed to applying the principles used very successfully in the limited solid angle LEP/SLC Silicon-Tungsten ECALs used for luminosity measurements to a full solid angle detector [4]. This approach is very attractive. Existing studies have characterized reasonably well the potential performance of the design studied for the TESLA TDR [5]. The main potential drawback is the cost, which may force the detector design to smaller radius, larger field and fewer sampling layers, as in the SiD approach.

To date, there has been relatively little work focused on ECAL concepts which are well matched to the goals of particle flow at large radius, where with TPC tracking one can envisage comprehensive charged particle flow. Given that there are good reasons to believe that a larger detector has a better physics potential, [6], this should be seen as an area of critical need.

The University of Kansas group has been working on developing ECAL concepts which have the potential to be competitive with Si-W in properties where Si-W excels while substantially more cost effective and offering complementary capabilities in terms of energy resolution and timing resolution. A more cost effective solution would naturally lead to the possibility of building a much larger detector which would be the most effective way of ensuring particle separation for particle flow measurements. This would naturally fit well into the large and huge detector design studies.

We have been studying compact hybrid sampling ECAL structures with Tungsten absorber, with both silicon sampling gaps and scintillator sampling gaps. This approach promises the cost-effective use of silicon for shower pattern recognition and position measurement, while using cheaper scintillator layers as the main sampling medium. With this approach we have studied the simpler configurations of only Silicon sampling and only Scintillator sampling too. The current favored approach for the scintillator sampling is using scintillator-tiles with wavelength shifting (WLS) fiber readout to “on-tile” Silicon-Photomultiplier photodetectors as employed in the CALICE MiniCAL [7]. The Silicon-PM has obvious advantages in terms of hermeticity, operation in B-field, and calibration (individual photo-electron peaks can be resolved). Features which need to be taken into account/mitigated are the noise and saturation characteristics.

We have been very encouraged by superb position resolution estimates for photons with Si-W sampling structures (300 μm for 1 GeV photons) assuming probably unrealistically small 1mm² pads [8] in a Si-W structure with a Moliere radius of 15 mm (see Figure 1). We are starting to envisage a new kind of particle-flow ECAL.

The essential issue about granularity is the separation of photons from charged tracks. This is best achieved by doing this separation at the longitudinal coordinate near which the photon converts. Our current ideas are to have a calorimeter which might consist of the following sections in depth:

- **PAIRCAL**: About 5 radiation lengths with Tungsten absorber and fine transverse granularity Silicon sampling layers (sampling at least every 0.5 radiation lengths). This device would pin-point the initial photon-conversion both in terms of transverse coordinate and longitudinal coordinate with very high efficiency. It may also be used to add some precise outer space points on high momentum tracks.

- **SHOWERCAL**: About 10 radiation lengths with Tungsten absorber and coarser transverse granularity Silicon sampling layers. The sampling would be at least every radiation length. More frequent sampling with some scintillator layers could be considered, but
Figure 1: Measured position resolution in one dimension for 1 GeV photons in a simulated Si-W calorimeter with 42 sampling layers (5/7 $X_0$ each) with 1mm$^2$ pads. Upper graph shows the results from the longitudinally integrated center-of-gravity of the shower with a resolution of 1.5 mm. The lower graph shows the results of a weighted “track-fit” to the first 12 layers, where layers close to the conversion point are given the most weight. A position resolution of 300 μm is achieved with 100% efficiency.
would need to be rather compact longitudinally. This device would do the bulk of the energy measuring while retaining excellent pattern recognition abilities before and after the EM shower maximum.

- **EM-TAILCAL**: About 15 radiation lengths of cheaper technology ECAL still with sampling frequency of at least every radiation length. The absorber could be Tungsten or Lead. Lead would have the advantage of a better radiation length to interaction length ratio, and being cheaper. Longitudinal compactness requirements would be less severe. This portion should also provide functionality at least as good as the chosen HCAL technology, but needs to be analog.

This kind of arrangement is better suited to detector integration than the hybrid designs we had been exploring. Each potentially different technology has its own radial space. However, the radial subdivision may also entail new difficulties with calibration and pattern recognition which will need to be investigated/minimized.

**Broader Impact**

The project will support participation of undergraduates in research.

Our on-going work with setting up cosmic-ray test facilities will be done in such a way that we can use the apparatus as part of an open-day type demonstration in conjunction with a diffusion cloud-chamber we recently acquired. This apparatus will allow the general public to see and hear cosmic-ray muons.

We are interested in making movies which depict what happens in an $e^+e^-$ interaction as the reaction products propagate through the detector and interact. The idea will be to capture images of a simulated event at appropriate time intervals after the interaction. Particularly relevant to this project, is to depict well the electromagnetic shower development.

**Status Report**

[Progress to Date]

We have made progress on many aspects of the project.

- We have studied the dependence of jet energy resolution on the intrinsic resolution of the tracker, the ECAL and the HCAL for all individual jet flavors. This study was carried out by Darius Gallagher (graduate student) under the supervision of Wilson. Initial results were reported at the Cornell, Summer 2003 meeting and are now written up in [2]

- Studies related to the importance of hermeticity in the detector design were described in the TESLA TDR by Wilson [9], and related results were reported in a plenary talk at the SLAC January 2004 ALCPG meeting [10]. Gallagher explored the ability to detect muons in low visible energy scenarios where hermetic forward coverage is essential and the beam-hole caused by a large crossing-angle can be a hard limitation. Gallagher has now graduated with an M.Sc.

- Undergraduate student, Eric Benavidez, has been instrumental in developing our GEANT4 capabilities under the supervision of Wilson. We have developed simulations related to the following:
  - optical tracking of photons in scintillator tiles
Figure 2: Dependence of energy resolution for 1 GeV photons on sampling layer thickness for 3 different ECAL configurations. Each ECAL has 30 radiation lengths of Tungsten absorber (ie. 105 mm of W).
simple sampling calorimeter test-beam geometries with arbitrary sampling media
pixelized sampling calorimeters. During 2005, we used the SLAC implementation of
GEANT4 for cross-checks, and are working on maintaining and extending the function-
ality of these types of simulation with up to date GEANT4 releases. Michael Ambroselli
(undergrad.) is working on this aspect at Univ. of Kansas.

• We have used these simulation tools to study several issues relevant to the ECAL de-
sign concept. These have been reported at the regular meetings both nationally and
internationally [11]. Some of the main results are the following:

Characterization of the energy resolution dependence on absorber and active mate-
rial thicknesses. Studies have been done for Si-W, Scint-W and hybrids with W absorber
and both Si and scintillator active layers. In particular we demonstrated that thicker
Silicon layers which lead to a higher sampling fraction benefit the energy resolution. An
example is shown in Figure 2.

We have investigated the position resolution for photons as a function of the cell
size. We have found, (as we expected), that cell sizes much smaller than the Moliere
radius, do indeed lead to much better position resolution. Even with 1mm pads, we still
found a resolution of pad-size/$\sqrt{2}$.

Study of the correlation between the Silicon and scintillator response in hybrid struc-
tures. An anti-correlation of as much as 20% was observed which goes in the direction
of improving the energy resolution compared to that which would be obtained with pure
Si-W or pure Scint.-W. This observation offers the possibility that novel media may lead
to larger (and more beneficial) anti-correlations.

Study of some of the dynamic range issues associated with measuring beam energy
electrons and photons at the highest center-of-mass energies.

Observation that studies reported by other groups were using tracking cutoffs in
the electromagnetic simulation which were affecting quantitatively their conclusions.
This problem was reported in Summer 2003, and reiterated this summer [12], and the
definitive time efficient fix from the GEANT4 electromagnetic processes team is expected
this December.

• We have continued to develop our lab., centered around a VME based data acquisition
system with multi-channel QDC’s and TDC’s for measurements with scintillator-based
detectors. Undergraduates Eric Benavidez and Jonathan van Eenwyk worked together
with Wilson on the commissioning of this system. Some of these developments are docu-
mented at [13]. We have been using this with a cosmic-ray trigger, as a set-up designed
for testing scintillator-tile assemblies. We are currently using this with scintillator tiles
from the OPAL experiment, described in [14]. We also have some internal conversion
electron sources which are being used in this study. Graduate student, Treaster, started
in late summer 2005, and is being trained in doing lab. measurements. During 2005, we
have added considerable functionality:

– Development of a motorized computer controlled X-Y stage for position scans (un-
dergraduate project with Stephen Floor)

– Development of LED driver circuit with precise pulse length adjustment (undergrad-
uate project with Chris Partick in collaboration with John Ledford (EE).

– Upgrading throughput of the VME data acquisition system by replacing parallel-
port VME controller with fiber-optic link controller. (Wilson and van Eenwyk)
- Commissioning of new VME scalers (van Eenwyk)
- Development of optical bench type functionality with neutral-density filters and diaphragms for additional light intensity control.
- Addition of new electronics modules including variable-gain amplifiers and variable-attenuation attenuators for amplitude measurement control
- Addition of new 1.5 GHz bandwidth 4-channel oscilloscope.

- Participation in all three established detector concept groups (LDC, SiD, GLD).
- Wilson has written a summary of the main issues involved in evaluating the calorimetry performance of detector design concepts [15] particularly in light of particle flow. Many of the issues discussed are very relevant to this status report.
- Photon Reconstruction studies: Eric Benavidez worked in summer 2005 on clustering algorithm studies related to photon reconstruction under the supervision of Wilson and in collaboration with Norman Graf at SLAC. Eric was a recipient of a McNair Scholarship (funding from Dept. of Education). Eric studied the performance of different clustering algorithms, in particular nearest-neighbor and fixed-cone algorithms and these studies are documented [16]. Together with Wilson and Hensel, they started exploring the use of the H-matrix approach (developed by Graf) for photon identification. Initial studies used only the longitudinal energy deposition information. The H-matrix approach uses the inverse covariance matrix of the fractional energy depositions to form a chi-squared for the goodness-of-fit of the observed cluster to the average behavior of an ensemble of photons.
- Kinematic fits. Wilson has investigated the potential for improving the energy resolution of $\pi^0$'s in hadronic jets by using 1-C kinematic fits of photon pairs to the $\pi^0$ mass. Studies [17, 18] indicate that there are excellent prospects for very significant improvements for detector designs similar to the current LDC and SiD concepts, where for typical $\pi^0$ energies in jets, the dominant contributions to the di-photon mass resolution come from the electromagnetic energy resolution rather than the opening angle measurement. Figure 3 illustrates the demonstrated improvement of around a factor of 2 in resolution for 5 GeV $\pi^0$'s assuming rather typical photon resolution characteristics. This is a direct consequence of the extremely precise measurement of the photon-pair opening angle enabled by fine granularity ECAL cell sizes. This study suggests that ultra-fine ECAL granularity may have significant performance merits.
- Hensel and Wilson participated in the SLAC simulation workshop (March 2005) and the Snowmass workshop [18, 19].
- Electromagnetic showers in high B-fields. Wilson realized that there are potential disadvantages to very high B-fields in terms of photon reconstruction. The high B-field increases the effective transverse shower size for photons beyond that expected from just the Moliere radius, potentially diminishing the effectiveness of using high B-field and small Moliere radius to compensate for small ECAL radius. A secondary effect seen in studies of kinematic fits is a bias in the azimuth measurement of photons which may be attributable to the charge asymmetry of secondary electrons compared to secondary positrons in EM showers, an effect which will be exacerbated with high B-field.
- Initiated work on detector design model incorporating the PAIRCAL/SHOWERCAL/EM-TAILCAL ideas with Mark Thomson. Strawman detector design is implemented in the org.Icsim framework (frankyang95) and events have been generated. Assistance from
5 GeV π0, 0.5 mrad opening angle resolution

![Graph showing energy resolution for 5 GeV π0's assuming ECAL fractional energy resolution of 16%/√E. Lower graph: Energy resolution from kinematic fit for 5 GeV π0's assuming opening angle resolution of 0.5 mrad. All decay angles are included.](image)

Figure 3: Upper graph: Simulated measured energy resolution for 5 GeV π0’s assuming ECAL fractional energy resolution of 16%/√E. Lower graph: Energy resolution from kinematic fit for 5 GeV π0’s assuming opening angle resolution of 0.5 mrad. All decay angles are included.
Norman Graf appreciated. The model has B-field of 3 T, and ECAL inner radius of 2.1 m, and as implemented uses Tungsten as absorber throughout. The ECAL sections total 40 sampling layers and a total thickness of 20 $X_0$ with uniform 0.5 $X_0$ sampling per layer. The first 10 sampling layers (PAIRCAL) have Silicon pads with 320 micron thickness, and pad size of 2.5 mm x 2.5 mm. The next 10 sampling layers (SHOWERCAL) have Silicon pads with 320 micron thickness and pad size of 1 cm x 1 cm. The remaining 20 layers are 2 mm thick 2 cm by 2 cm scintillator tiles. This is followed by 50 layers of 2 mm thick 4 cm by 4 cm scintillator tiles. Dimensions were chosen to be technically feasible, and does not yet take advantage of potential new technologies like MAPS for the PAIRCAL.

- Particle Flow Algorithm Studies: We have contributed to the photon reconstruction effort which has been used in the orglesim based work, led by Norman Graf. Particularly in the context of investigating the particle flow performance of various detectors including issues like charged particle tracking in a TPC, and in contributing to studies for LDC, we felt it was necessary to develop some expertise with the MARLIN-based reconstruction code.

- Particle Flow Discussion: Led prioritization discussion at Snowmass of various detector issues related to particle flow and helped initiate relevant studies in collaboration with Mark Thomson, Felix Sefkow, Norman Graf, Steve Magill. Many of the main issues are starting to be studied rather seriously in several of the regions.

- We have been in communication with a number of potential collaborators, whom we are interested in collaborating with on this or related projects.
  
  M. Ronan, (LBL) : large detector concept
  R. Frey, D. Strom (Oregon) : Si-W
  J.C. Brient, (Ecole Polytechnique) : Si-W ECAL
  M. Thomson, D.R. Ward, (Cambridge), calorimeter reconstruction
  K. Kawagoe (Kobe), T. Takeshita (Shinsyu), scintillating-tile ECAL
  B. Dolgoshein (MePHI), M. Danilov (ITEP), Silicon-PM
  V. Korbel, F. Sefkow (DESY), tile-HCAL applied to ECAL
  V. Zutshi (NIU)
  S. Kuhlmann, S Magill (Argonne)
  P. Checchia (Padova)
  D. Onoprienko, E. von Toerne, T. Bolton (Kansas State)
  P. Baringer, A. Bean, D. Besson (Kansas)
  N. Graf, A. Johnson, R. Cassell, J. McCormick (SLAC)
  F. Gaede, A. Raspereza (DESY)

FY2006 Project Activities and Deliverables

We will continue investigations of the performance characteristics of various ECAL concepts. A particular priority will be to quantify the relative importance in realistic particle flow algorithms of charged-particle/photon separation compared to charged-particle/neutral hadron separation. This is critical for assessing the granularity requirements of the ECAL compared to the HCAL. This amounts to gaining a quantitative understanding of the various sources of "sigma confusion".
We will extend the study of kinematic fits to $\pi^0$ candidates to assessing the performance gains expected of such kinematic fits in a hadronic jet environment. In hadronic jets, typically 92% of photons originate from $\pi^0$s but there are around 5 $\pi^0$s per jet. An important aspect will be to develop an appropriate algorithm for testing different ways to assign photons to $\pi^0$ candidates. This should be easier than one might naively think in that the symmetric decays have the biggest potential improvement, and if one starts from the most energetic photon, there will be relatively few potential partner photons giving a reasonable fit probability. We expect that the photonic energy contribution to the jet resolution will be improved substantially.

We will work on the photon reconstruction for particle flow algorithms. In calendar year 2006, we expect substantial contributions from Benavidez, Hensel, Treaster and Wilson. This activity should be beneficial to all ECAL concepts and detector design concepts. Deliverables will include characterization of the photon reconstruction performance. We are very keen to also investigate the quality of reconstruction of photons inside hadronic jets (i.e. near interacting charged particles). A useful figure of merit, which factorizes out neutral hadron effects, is the reconstructed visible energy in hadronic $Z$ decays where there are no neutral hadronically interacting particles, nor neutrinos. For these studies to have an impact on the global detector optimization in the context of particle flow, we plan to develop our ability to contribute to characterizing the overall detector performance using the state-of-the-art particle flow algorithms taking advantage of and contributing to software developments in all regions.

We will investigate calibration issues for longitudinally subdivided ECAL sections. This will involve sampling corrections as a function of shower depth/age, and will necessitate reconstruction of the photon conversion point shower by shower.

We plan to characterize the expected photon response over the full solid angle paying particular attention to the regions where hermeticity might be compromised.

We are very interested in getting involved in test-beam tests of particularly photon/charged-hadron separation, and anticipate participating in current Si-W projects.

**FY 2007 Project Activities and Deliverables**

This proposal is targeted at the development of an electromagnetic calorimeter design concept in a timely manner. However it is probable that many of the issues targeted in FY2006 will require further investigation in FY2007 or lead to other compelling related areas of investigation. We foresee future funding requests for the validation of design choices and construction and testing of a prototype once we have converged on an electromagnetic calorimeter design concept. The outlined budget for both fiscal years assumes little growth in budgets. If substantial growth were possible, the project would most benefit from additional funding which would permit dedicated work by a post-doc, or dedicated faculty work during the semester.

**Budget justification:** University of Kansas

The budget and scope we have outlined for this project is primarily for the design of a concept. In this respect a majority of the costs are associated with personnel (in the form of undergraduate and graduate research support), and the support for travel. The travel will be associated both with software development, particularly in collaboration with SLAC, and also work related to the detector design concept which will involve travel to discuss with collaborators both in Europe and Asia, and participation at future workshops.
The materials and supplies items are associated with fabrication of scintillating-tile assemblies and associated photo-detectors.

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

**Institution: University of Kansas**

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**References**


12
6.14: Construction of a Prototype Hadronic Calorimeter with Digital Readout

(renewal)

Calorimetry

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Institution(s)
Argonne
Boston University
Chicago
Fermilab
Iowa

FY05 award: 18,000

New funds requested
FY06 request: 105,000
Construction of a Prototype Hadronic Calorimeter with Digital Readout (LCRD)

Calorimetry

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Argonne National Laboratory
Boston University
University of Chicago
Fermi National Accelerator Laboratory
University of Iowa

FY2006: $105,000
**Project name**

Construction of a Prototype Section of a Digital Hadron Calorimeter

**Classification (accelerator/detector:subsystem)**

Detector

**Institution(s) and personnel**

Argonne National Laboratory: Gary Drake (electronics engineer), Victor Guarino (mechanical engineer), Steve Kuhlmann (staff scientist), Steve Magill (staff scientist), Brian Musgrave (scientist emeritus), José Repond (staff scientist), Dave Underwood (staff scientist), Harry Weerts (staff scientist), Barry Wicklund (staff scientist), Lei Xia (postdoctoral research associate)

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

University of Chicago: Mark Oreglia (professor)

Fermilab: Marcel Demarteau (staff scientist), Dmitri Denisov (staff scientist), James Hoff (electronics engineer), Abderrezak Mekkaoui (electronics engineer), Adam Para (staff scientist), Ray Yarema (electronics engineer)

University of Iowa: Edwin Norbeck (professor), Yasar Onel (professor)

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Project overview

We propose to construct a 1 m³ prototype section of a digital hadron calorimeter. The section will consist of 40 steel plates, each 20 mm thick, interleaved with Resistive Plate Chambers (RPCs) as the active medium.

This project is part of the design of a detector for the International Linear Collider (ILC). At the ILC, in order to disentangle W and Z bosons via their hadronic decay into a pair of jets, jet energy resolutions of the order of $30\% \sqrt{E_{\text{jet}}}$ or better are required. Simulation studies have shown that with the help of Particle Flow Algorithms (PFAs) these types of resolutions can be achieved. Contrary to conventional methods relying solely on the calorimetric measurements, PFAs attempt to measure each final state particle in a jet separately utilizing the detector component able to provide the best momentum/energy resolution. So, charged particles are measured by the tracking detectors imbedded in a strong magnetic field, photons are measured with the electromagnetic calorimeter and neutral hadrons, i.e. neutrons and $K_L^0$, are measured with the electromagnetic and hadronic calorimeters. The major challenge of this approach is the separation of energy clusters in the calorimeter originating from charged and neutral particles. In order to keep this contribution, commonly named the ‘confusion’ term, to the resolution small the readout of the RPCs will be extremely finely segmented, 1 cm² laterally and layer-by-layer longitudinally. The optimal segmentation for the ILC detector will be determined after evaluation of the test beam results and the subsequent tuning of the simulation of hadronic showers (see below).

The electronic readout will be reduced to a single bit per readout channel (digital readout). Simulation studies have shown that a digital readout of finely segmented pads is able to preserve, if not improve, the energy resolution of single hadrons, traditionally measured with analog readout of calorimeter towers. The readout system will be entirely compatible with the readout of Gas Electron Multiplier chambers (GEMs), which are also being considered for digital hadron calorimetry [1].

The proposed digital hadron calorimeter (DHCAL) for the ILC is an entirely novel idea, which will be substantiated with measurements in test beams at Fermilab. The tests will be either in stand-alone mode or together with a prototype of the electromagnetic calorimeter placed in front of the DHCAL. The proposed technology of a digital hadron calorimeter with RPCs is equally applicable to all three ILC detector design efforts, namely the SiD, the LDC, and the GDC concepts.

The major reasons for constructing a prototype section of a DHCAL and subsequent tests in particle beams are summarized in the following. This effort is arguably the most important R&D project related to the development of an ILC detector:

- **Test of a calorimeter with RPCs**: even though RPCs have been employed in a large number of HEP experiments, to date no calorimeter with finely segmented readout using RPCs as active medium has been built and tested. Our tests will validate the use of RPCs in calorimetry.
- **Tests of the novel idea of a DHCAL**: in simulation studies of a DHCAL the resolution obtained for single hadrons is comparable to the results obtained with analog readout. Experimental verification of this and validation of the concept of a DHCAL is needed.

- **Study of design parameters**: measurements with different configurations of the prototype section will provide a better understanding of the dependence of the response on the various design parameters, such as the choice of absorber, the size of the active gap, the segmentation of the readout, etc.

- **Measurement of hadronic showers**: traditional calorimeters measure energy with a coarse segmentation, thus integrating over large volumes. Our DHCAL prototype section will measure hadronic showers with unprecedented spatial resolution and provide very detailed information on hadronic showers.

- **Validation of Monte Carlo simulation of hadronic showers**: the measurements obtained in particle beams will be essential to validate the Monte Carlo simulation of hadronic showers. To date differences of up to 60% are observed when comparing the results on shower shapes based on different MC models of the hadronic shower, see Figure 1. The design of a detector for the International Linear Collider is driven by the application of Particle Flow Algorithms for the measurement of hadronic jets. A realistic simulation of hadronic showers is a prerequisite for the development of a reliable design of such a detector.

- **Comparison with an Analog Hadron Calorimeter**: Currently the CALICE collaboration [3] is assembling a prototype section of a hadron calorimeter (AHCAL) using scintillator tiles and analog readout. The lateral size of the tiles is about a factor of 10 larger than the readout pads of the DHCAL. A technology choice for the hadron calorimeter for an ILC detector will be based on a detailed comparison of the performance of the AHCAL and DHCAL prototypes.

---

![Figure 1](image.png)

**Figure 1.** Comparison of the shower radius in a hadron calorimeter as predicted with fifteen different MC models of the hadronic showers normalized to the result with G4-FTFP.
Studies of the performance of a digital hadron calorimeter

Detailed Monte Carlo studies based on GEANT4 are being performed to understand the response of calorimeters, develop PFAs and to optimize the design of an ILC detector for the measurement of hadronic jets. The studies summarized in the following are based on the SiD concept [3].

The SiD concept study defined a baseline design for their detector as a starting point for subsequent design studies. The baseline design features a six layer vertex detector, a five layer silicon tracking detector, a Silicon-tungsten electromagnetic calorimeter with 0.16 cm² readout cells, a RPC-Steel hadronic calorimeter with 1 cm² readout pads, a superconducting coil providing a 5 Tesla fields and an instrumented return yoke.

The single particle response for 5 GeV $\pi^+$ is shown in Figure 2 a) using analog readout and b) using 1 cm² pads with digital readout. Digital readout is clearly able to preserve the resolution. In addition, due to its inherent insensitivity to Landau fluctuations, the response measured with digital readout is more symmetric and does not feature a tail towards larger values.

Several groups are involved in the development of PFAs using the SiD baseline design. The PFAs contain the following major ingredients: clustering of the calorimeter cells, track-cluster matching, identification of photons, identification of neutral hadronic clusters, and assignment of cluster fragments to charged or neutral particles. First results have been presented at conferences and workshop. As an example, Figure 3 shows the reconstructed mass obtained in $e^+e^- \rightarrow Z^0 \rightarrow 2 \text{ jets}$. The central part of the response is fit to a Gaussian with a width of $3.2 \text{ GeV}$, corresponding to approximately $\sigma/E = 33%/\sqrt{E_{\text{jet}}}$, and containing 60% of the events. Even though further improvements are necessary to reduce the tails, these results demonstrate, within the credibility of the simulation of

Figure 2. Response of a hadron calorimeter to 5 GeV $\pi^+$: a) with analog readout of scintillator tiles, $\sigma/\mu \sim 22\%$, and b) with digital readout of 1 cm² pads, $\sigma/\mu \sim 19\%$. 

Figure 3. Reconstructed mass obtained in $e^+e^- \rightarrow Z^0 \rightarrow 2 \text{ jets}$. The central part of the response is fit to a Gaussian with a width of $3.2 \text{ GeV}$, corresponding to approximately $\sigma/E = 33%/\sqrt{E_{\text{jet}}}$, and containing 60% of the events. Even though further improvements are necessary to reduce the tails, these results demonstrate, within the credibility of the simulation of...
hadronic showers, that jet energies can be measured with a resolution significantly better than the $50 - 100\%/\sqrt{E_{\text{jet}}}$ obtained in calorimetric measurements.

Figure 3. Reconstructed mass of dijets in $e^+e^- \rightarrow Z^0 \rightarrow 2$ jets events. The width of the central Gaussian is 3.2 GeV and contains approximately 60% of the events.
Description of the 1 m³ Prototype Section

General description

The planned prototype section features 40 layers each with an area of 1 m². The physical extend is approximately one meter in depth. Simulation studies showed that 98% of the energy of a 10 GeV $\pi^+$ is contained in the prototype section; see Figure 4 for a visual impression of the spatial distribution of the energy deposition of a hadronic shower.

![Figure 4. Average energy deposition from a 10 GeV $\pi^+$ in the prototype electromagnetic and hadronic calorimeters.](image)

Mechanical structure

The mechanical structure consists of a movable table and the 40 absorber plates. The latter are made of stainless steel with a thickness of 16 mm and an area of 1 m². They are suspended such, that the gap between neighboring plates can be adjusted from 0.5 to 1 cm, depending on the thickness of the active elements.

The table provides all the flexibility of positioning necessary in a test beam, such that every cell in the prototype section can be exposed to a muon beam without having to move the beam. In addition, the table can be rotated along a vertical axis for studies of the response of particles entering the calorimeter at an angle. Figure 5 shows the three-dimensional design of the table.
The design and construction of the table are the responsibility of DESY in Hamburg, Germany.

![Image](image1.png)

Figure 5. Three-dimensional design of the table for beam tests including stack of absorber plates of the hadron calorimeter.

**Active medium**

Resistive Plate Chambers (RPCs) with small readout pads are an ideal candidate for a hadron calorimeter designed to optimize the application of PFA. They can provide the segmentation of the readout pads of the order of 1 to 4 cm$^2$, which is necessary to keep the ‘confusion’ term small, and they can be built to fit small active gaps (less than 10 mm) to maintain a small lateral shower size. Glass RPCs have been found to be stable in operation for long periods of time, especially when run in avalanche mode, and the rate capabilities are adequate for the ILC and for test beam studies of hadronic showers. RPCs are inexpensive to build since most parts are available commercially. The readout electronics can be simplified to a one-bit per pad resolution. Signals in avalanche mode are large enough to simplify the design of the front-end electronics.

Figure 6 shows a schematic diagram of a single-gap RPC. The chamber consists of two plates with high electrical resistance. Readily available window glass of thickness 0.8 to 1.1 mm will be used to construct the RPC. High voltage is applied to a resistance coating on the outside of the glass plates. The resistance of this coating must be low enough to re-charge the glass locally after a signal hit, and high enough to allow the electric field of the electron avalanche in the gas to reach the external signal pick-up pads. The glass plates enclose a gas volume in which ionization and electron multiplication takes place. Particles traversing the gas gap ionize the gas, creating an avalanche of electrons drifting towards the glass plate at positive high voltage. The signal is picked up inductively with pads located on the outside of the glass.
For the prototype section each layer with an area of $1 \text{ m}^2$ will be equipped with three chambers with an area of $32\times96 \text{ cm}^2$. Each chamber contains 3072 readout pads.

Since digital hadron calorimetry is a new approach, additional beam tests with Gas Electron Multiplier chambers (GEMs) replacing some layers of RPCs in the prototype section are planned. Differences in pad-to-pad cross talk, rate capability, operational stability, etc. will be studied. The electronic readout system is designed such that both RPCs and GEMs can be read out with the same front-end and back-end system.

**Electronic readout system**

Considerable effort is dedicated to the development of the electronic readout system, a challenge by itself, given the large number of channels, of order $4\times10^5$ for the prototype section and $5\times10^7$ for the DHCAL of an ILC detector. The readout electronics is suitable for both the RPC and the GEM readout. The gain of the front-end is adjustable to accommodate the different signal sizes of the two devices. Particular care was devoted to keeping the cost per channel as small as possible.

The electronic readout system consists of several stages: a) the front-end ASIC; b) the front-end boards; c) the data concentrator; d) the super concentrators; e) a VME-based data collector; and e) a trigger and timing system. In the following we briefly describe the individual stages:

a) The front-end ASIC receives signals from 64 individual pads. The signals are shaped, amplified, and discriminated. The resulting hit patterns are time stamped and stored at a speed of 10 MHz. In triggered mode, an external trigger selects the events to be passed on to the data concentrator. In triggerless mode any hit pattern with at least one hit will be written out. The ASICs will be located directly on the PC boards containing the readout pads of the chambers.

b) The front-end boards are located directly on the chambers. Two boards with dimensions of $32\times48 \text{ cm}^2$ are required per chamber. The boards contain the readout pad and transfer lines to the ASIC (analog signals) as well as the path for the digital output signals from the ASIC. Special care is necessary for proper
shielding of the analog circuitry from digital noise. The boards contain 8 – 10 layers.

c) The data concentrators receive data from 12 individual ASICs. They mainly consist of FPGAs and will be located on the side of the 1 m³ prototype section of the hadronic calorimeter.

d) The super concentrator further multiplexes the readout by reading out six data concentrators. Their design is similar to the data concentrators.

e) The data collector is VME–based and receives the output of the super concentrators. Each card will connect to 12 individual data concentrators. The system specifications are very similar to the recently developed system for the MINOS test beam effort.

f) The trigger system distributes the trigger information to the data concentrators. The timing system provides the clocks and clock resets of the readout system.
Planned measurements in the Fermilab test beam

We plan to expose the prototype DHCAL section to the MTB6 test beam at Fermilab. The calorimeter will be tested both in standalone mode as well as in combination with a prototype electromagnetic calorimeter located in front. The latter will be provided initially by the CALICE collaboration [3] and later by the SLAC-Oregon group [4]. A tail-catcher [5] consisting of steel plates and scintillator strips will be placed behind the DHCAL prototype. In the following we briefly describe the planned test beam activities:

Standalone tests of the DHCAL prototype including the tail catcher

Standalone tests of the prototype section of the DHCAL will be performed in the following configurations:

- **Energy Scans with Pions and Protons**: Single pion responses, linearity and energy resolution will be measured using a wide range of momenta (from 1 GeV/c up to 66 GeV/c). The response to protons over the entire momentum range (up to 120 GeV/c) will be measured as well.

- **Incident Angle Scans**: Measurements with at least three different angles of incidence will be performed. The angles will be changed by rotating the table with respect to the beam and offsetting the calorimeter structure in depth in order to optimize the lateral containment. These tests are foreseen using at least two different energy settings.

- **Muon Responses**: Measurements with momentum tagged (3 – 20 GeV/c) muons will be performed for muon detection efficiency measurement, testing reconstruction codes and developing calorimeter tracking algorithms.

- **Calibration Runs**: For calibration purposes, measurements with defocused muons will be performed at regular intervals during the testing period.

Combined tests of electromagnetic and hadronic calorimeters including tail catchers

The following test program is foreseen for the combination of ECAL and DHCAL prototypes:

- **Electron Energy Scans**: These tests require electrons with the highest achievable energy, to provide a data set with combined ECAL and DHCAL information.

- **Energy Scans with Pions and Protons**: Single pion responses, linearity and energy resolution will be measured using a wide range of momenta (1 – 66 GeV/c). The response to protons over the entire momentum range (up to 120 GeV/c) will be measured as well.
- **Incident Angle Scans**: Measurements with at least three different angles of incidence will be performed. These tests are foreseen using at least two different energy settings.

- **Muon Responses**: Measurements with momentum tagged (3 – 20 GeV/c) muons will be performed for testing MIP reconstruction codes and developing calorimeter tracking algorithms.

- **Calibration Runs**: For calibration purposes, measurements with defocused muons will be performed at regular intervals during the testing period.

These tests will start in 2007 and last until approximately the end of 2008. The CALICE collaboration plans to use the same beam line for measurements with their electromagnetic and analog hadron calorimeter prototypes. Comparison of the results of the analog and digital hadron calorimeters using the same beam line (and absorber configuration) will be essential for deciding on the technology to be used for the ILC detector’s hadron calorimeter.

Recently Fermilab reviewed [6] the feasibility of modifications to the MTBF beam line as requested by the CALICE collaboration. The decision was taken to move the target for the production of secondary particles closer to the experimental area, thus increasing the rate of low energy pions by several orders of magnitude.
Current status of the project

R&D on Resistive Plate Chambers

Work on developing RPCs for application in a hadron calorimeter has been underway for the past two to three years at Argonne National Laboratory. A number of single- and multi-gap chambers have been built and have been tested thoroughly with sources and cosmic rays. The chambers vary in design, containing one to three glass plates and resistive coats of different surface resistivity. Table I lists the different measurements performed on the chambers. For more details see [7].

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal characterization</td>
<td>Completed</td>
</tr>
<tr>
<td>HV dependence</td>
<td>Completed</td>
</tr>
<tr>
<td>Single pad efficiencies</td>
<td>Completed</td>
</tr>
<tr>
<td>Geometrical efficiencies</td>
<td>Completed</td>
</tr>
<tr>
<td>Tests with different gases</td>
<td>Completed</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>Completed</td>
</tr>
<tr>
<td>Multipad efficiencies</td>
<td>Completed</td>
</tr>
<tr>
<td>Hit multiplicities</td>
<td>Completed</td>
</tr>
<tr>
<td>Noise rates</td>
<td>Completed</td>
</tr>
<tr>
<td>Rate capability (source and cosmics)</td>
<td>Completed</td>
</tr>
<tr>
<td>Tests in 5 T magnetic field</td>
<td>Completed by other groups</td>
</tr>
<tr>
<td>Tests in particle beams</td>
<td>Planned</td>
</tr>
<tr>
<td>Long term tests</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Design of larger chamber</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>

Table I. List of measurements performed on the ANL prototype RPCs.

As an example of the measurements performed with the prototype chambers, Figure 7 shows the hit multiplicity versus detection efficiency for chambers operating at different high voltages.

Based on these tests we have developed a base design of RPCs for the digital hadron calorimeter. We are confident that these chambers will perform as required for the prototype beam tests.

R&D on the electronic readout system

A conceptual design of the electronic readout system for the prototype section has been developed and documented [8].

The ASICs have been designed by Fermilab in collaboration with ANL. A first prototype run is currently being evaluated. A computer controlled test board has been designed and fabricated, see Figure 8. Several changes to the analog part of the circuitry are planned.
requiring a second iteration before production of the required 8000 chips for the prototype section can be envisaged.

Figure 7. Multiplicity as a function of single particle detection efficiency for a RPC operated at three different high voltage settings.

Figure 8. Photograph of DCAL test boards: board containing DCAL chip (left) and computer interface board (right).
A prototype of the Front-end board has been fabricated. The board is designed specifically for the study of the cross-talk between digital (LVDS signals) and analog signals. The measurements indicate a small cross-talk, of the order of 10 – 20 fC, which is within the range of acceptable values for operation with RPCs. Due to the significantly smaller signal size, of the order of a factor of 10, further reductions of the cross-talk are necessary for the readout of GEMs.

Design work on the data concentrators and the VME-based data collector has initiated. The possibility of using the data collector system (CRC-boards) of the analog hadron calorimeter prototype is being investigated.

**Preparation for the test beam**

Discussions with the management of Fermilab and the people responsible for the test beam have initiated some time ago. A detailed technical note [9] written by the worldwide ILC calorimeter test beam group was submitted to Fermilab in February 2005. The note details the goals and requirements of the test beam program.

As a further step towards a test beam program at Fermilab, the ANL and University of Iowa groups are planning on testing single layers of RPCs in the MTBF test beam. These tests will be particularly useful in determining the particle rates for pions as a function of energy. The groups plan to perform measurements of the single particle detection efficiency as a function of incident particle rates. A Memorandum of Understanding between ANL, University of Iowa and Fermilab is in preparation. The tests are planned for early 2006.
Construction of the 1 m$^3$ prototype section

Construction of RPCs

To fully equip the 1m$^3$ prototype section a total of 120 RPCs are necessary. The chambers will be mounted on a strong – back, a 4 mm copper plate. The perimeter of the strong – back will be equipped with cooling tubes to cool the heat generated by the ASICs located on the front-end boards.

A quality assurance procedure to ensure the high quality of the chambers and uniform response will be devised. The procedure will include tests of the gas tightness as well as measurements of the single particle detection efficiency.

Construction of the electronic readout system

Table II lists the different parts of the readout system and the number of units needed to fully equip the prototype section. Each unit will be thoroughly tested in computer controlled test fixtures.

<table>
<thead>
<tr>
<th>Component</th>
<th>#/chamber</th>
<th>#/plane</th>
<th>#channels/unit</th>
<th>Total # units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planes</td>
<td>0.333</td>
<td>1</td>
<td>9216</td>
<td>40</td>
</tr>
<tr>
<td>Chambers</td>
<td>1</td>
<td>3</td>
<td>3072</td>
<td>120</td>
</tr>
<tr>
<td>DCAL ASICs</td>
<td>24</td>
<td>144</td>
<td>64</td>
<td>5760</td>
</tr>
<tr>
<td>Front-end boards</td>
<td>2</td>
<td>6</td>
<td>1536</td>
<td>240</td>
</tr>
<tr>
<td>Data concentrators</td>
<td>4</td>
<td>12</td>
<td>768</td>
<td>480</td>
</tr>
<tr>
<td>Super concentrators</td>
<td>0.667</td>
<td>2</td>
<td>4608</td>
<td>80</td>
</tr>
<tr>
<td>Data collectors</td>
<td>-</td>
<td>0.166</td>
<td>55,296</td>
<td>7</td>
</tr>
<tr>
<td>VME crates</td>
<td>-</td>
<td>-</td>
<td>387,072</td>
<td>1</td>
</tr>
</tbody>
</table>

Table II. List of the parts of the electronic readout system.

Responsibilities as assigned to institutions participating in the project

Table III summarizes the responsibilities as assigned to the different institutions participating in the project.

<table>
<thead>
<tr>
<th>Argonne National Laboratory</th>
<th>Construction of chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overall electronic system design</td>
</tr>
<tr>
<td></td>
<td>Test fixtures for front-end ASIC</td>
</tr>
<tr>
<td></td>
<td>VME based data collector system</td>
</tr>
<tr>
<td></td>
<td>Transportation of RPCs to test beam</td>
</tr>
<tr>
<td>Boston</td>
<td>VME based data collector system</td>
</tr>
<tr>
<td>Chicago</td>
<td>Data concentrator boards</td>
</tr>
<tr>
<td>DESY</td>
<td>Mechanical structure</td>
</tr>
<tr>
<td>FNAL</td>
<td>Front-end ASICs</td>
</tr>
<tr>
<td></td>
<td>Front-end readout boards</td>
</tr>
</tbody>
</table>
Table III. Responsibility for the construction and testing of the various subsystems of the prototype DHCAL section.

<table>
<thead>
<tr>
<th>Iowa</th>
<th>High voltage distribution system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas distribution system</td>
</tr>
<tr>
<td>UTA*</td>
<td>Timing and triggering system</td>
</tr>
</tbody>
</table>

* not part of this proposal
Budget and budget justification

Table IV summarizes the projected M&S costs for the construction of the prototype section.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Contingency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPC mechanics</td>
<td>32,200</td>
<td>9,500</td>
<td>41,700</td>
</tr>
<tr>
<td>DCAL ASIC</td>
<td>240,000</td>
<td>11,600</td>
<td>251,600</td>
</tr>
<tr>
<td>Front-end boards</td>
<td>110,000</td>
<td>55,000</td>
<td>165,000</td>
</tr>
<tr>
<td>Data concentrators</td>
<td>106,000</td>
<td>53,000</td>
<td>159,000</td>
</tr>
<tr>
<td>Super concentrators</td>
<td>25,000</td>
<td>12,500</td>
<td>37,500</td>
</tr>
<tr>
<td>VME data collectors</td>
<td>46,500</td>
<td>19,250</td>
<td>65,750</td>
</tr>
<tr>
<td>Timing system</td>
<td>20,000</td>
<td>10,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Power supplies</td>
<td>20,000</td>
<td>10,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Cables</td>
<td>27,500</td>
<td>13,750</td>
<td>41,250</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>627,200</td>
<td>194,600</td>
<td>811,800</td>
</tr>
</tbody>
</table>

Table IV. Summary of the M&S costs for the prototype section.

The following comments regarding the costs in Table III need to be made:

- The costs for the RPC mechanics include a gas distribution system
- The cost for the DCAL ASIC includes a second prototype run
- The power supplies include both low and high voltage power supplies

Table V summarizes the expected labor costs based on the current rates at ANL and FNAL.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Contingency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical assembly</td>
<td>87,600</td>
<td>21,900</td>
<td>109,500</td>
</tr>
<tr>
<td>DCAL ASIC</td>
<td>16,200</td>
<td>8,100</td>
<td>24,300</td>
</tr>
<tr>
<td>Front-end boards</td>
<td>31,625</td>
<td>15,800</td>
<td>47,425</td>
</tr>
<tr>
<td>Data concentrators</td>
<td>60,950</td>
<td>30,475</td>
<td>91,425</td>
</tr>
<tr>
<td>Super concentrators</td>
<td>11,500</td>
<td>5,750</td>
<td>17,250</td>
</tr>
<tr>
<td>VME data collector</td>
<td>35,200</td>
<td>17,600</td>
<td>52,800</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>243,075</td>
<td>99,625</td>
<td>342,700</td>
</tr>
</tbody>
</table>

Table V. Summary of labor costs based on current labor rates at ANL and FNAL.

The total cost of project, including labor, M&S and contingency, is $1,164,500. The cost of the mechanical structure and beam test table is not included in this estimate, since it will be provided by the DESY laboratory.

Table VI lists the financial contributions expected from participating institutes and others.
Table VI. Summary of the financial contributions from participating institutions and others.

Argonne’s contribution will be to provide the labor for assembling the RPCs and to check-out the different parts of the electronic readout system. The participating universities will provide the labor to check out the electronic components for which they have assumed responsibilities, see Table VI.

Table VII, finally, lists the amounts still to be funded over the period of the next two years.

Table VIII. Summary of funds still needed for the construction of the prototype DHCAL section.

We realize that the outstanding amount of about $400,000 (excluding contingencies) can not be funded entirely out of LCRD funds. The possibility of receiving funding through supplemental proposals to the DOE is being explored. The current proposal, therefore, requests funding of the order of $105,000 through the LCRD funds, which is commensurate with the overall size of the LCRD funds.

**Broader Impact**

The challenges raised by the linear collider physics program promote the development of new detector technologies. The necessary fine granularity of the hadron calorimeter requires a novel technical approach. The proposed digital hadron calorimeter with Resistive Plate Chambers as active medium fulfills the physics criteria, but has never been built and tested before.

These technological challenges require close collaboration between industries, universities and national laboratories. The project involves a number of graduate and undergraduate students associated with the universities participating in this proposal. At Argonne the project will attract participation from high school teachers and summer students.
The detailed measurements of the response to single particles will further the understanding of hadronic showers and provide a unique data base for comparison with simulation. The results from this program will be disseminated through national and international conferences and workshops and published in peer-reviewed journals.
References

6.16: Dual-Readout Calorimetry for the ILC
(renewal)

Calorimetry

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Richard.Wigmans@ttu.edu
(806) 742-3779

Institution(s)
U.C. San Diego
Iowa State
Texas Tech
INFN Trieste
Pavia
Rome
Cosenza (Italy)

FY05 award: 22,500

New funds requested
FY06 request: 71,500
FY07 request: 58,400
Project Leader
Name of project leader Dr. Richard Wigmans
Richard.Wigmans@ttu.edu
(806) 742-3779

Project Overview
The DREAM (Dual-REAadout Module) calorimeter was developed as a device that would make it possible to perform high-precision measurements of hadrons and hadron jets, while not subject to the limitations imposed by the requirements for compensating calorimetry, and thus addresses one of the most critical Detector R&D needs of the ILC.

The DREAM detector is based on a copper absorber structure, equipped with two types of active media which measure complementary characteristics of the shower development. Scintillating fibers measure the total energy deposited by the shower particles, while Čerenkov light is only produced by the charged, relativistic shower particles. Since the latter are almost exclusively found in the electromagnetic (emi) shower component (dominated by $\pi^0$s produced in hadronic showers), a comparison of the two signals makes it possible to measure the energy fraction carried by this component, $f_{em}$, event by event. As a result, the effects of fluctuations in this component, which are responsible for all the traditional problems in non-compensating calorimeters (non-linearity, poor energy resolution, non-Gaussian response function), can be eliminated, and an important improvement in the hadronic performance is achieved.

In the context of the approved ILC R&D component of this project, we concentrate on two aspects:
1. **The electromagnetic section.** The benefits of the dual-readout method are by no means limited to fiber calorimeters. Any medium that generates both Čerenkov light and scintillation light can be used for this purpose. And since the sampling fraction does not have to have a specific value (as in compensating calorimeters), there is no reason why a calorimeter based on the dual-readout principle could not have excellent electromagnetic energy resolution. In particular, homogeneous detectors generating both scintillation and Čerenkov light are an attractive option. The challenge is then of course to separate these two types of signals. This is the main topic of our studies.

2. **The readout of a fiber-based hadronic section.** The fiber-based DREAM calorimeter could in principle form an excellent and cost-effective solution for the hadronic section of a calorimeter system for a Linear Collider experiment. However, the readout of its many fibers would present a substantial challenge. The scintillating fibers and the Čerenkov fibers have to be grouped in separate bunches for readout by their respective light detectors. The prototype that was extensively tested in particle beams was equipped with standard photomultipliers (PMTs), two per tower. An attractive readout alternative for application in an ILC detector is offered by silicon photomultipliers. We want to equip the existing DREAM calorimeter with such a readout and study its performance.

**Status Report**

Because of the very limited ILC Detector R&D funds received, we have had to choose what to concentrate on in FY05/06, and we have decided that the electromagnetic section would be our main priority. This decision was also inspired by the fact that several other groups in the ILC Detector R&D program are working on SiPMs. We would like to wait and take advantage of their results before embarking on the hadronic-readout program. We will reconsider this situation again one year from now.

The current status of our project can be summarized as follows.

- We have concluded the analysis of dedicated measurements with the existing DREAM module, aimed at unraveling mixed scintillation/Čerenkov signals into their components. We used the time structure of the signals and the angular photon distribution for this purpose. This analysis was recently published:

- We have started studies to find suitable candidates for a homogenous electromagnetic calorimeter that can be used in a dual-readout mode. There are two possible configurations:
  1) A relatively poor scintillator that generates sufficient Čerenkov light, and whose scintillating properties are conveniently different from those of the Čerenkov light. PbWO$_4$ is the prime candidate. We are looking into ways to selectively reduce the scintillation light in this crystals.
  2) A suitable Čerenkov detector that can be doped with a proper scintillation agent. Lead glass and PbF$_2$ are the leading candidates.
• We have requested and been allocated beam time at the CERN SPS during the summer of 2006 to perform tests with the selected detectors. If time permits, these tests will be carried out in conjunction with the existing DREAM module, which will then serve as hadronic section in the measurements. Most likely, the latter measurements will be continued and completed in 2007.

• We have enlarged our collaboration with a number of Italian groups (Pavia, Rome, Cosenza), who have agreed to take prime responsibility for preparing these beam tests at CERN.

FY2006 Project Activities and Deliverables

Project activities and milestones:

• Order candidate detector samples (see previous section, January 2006)
• Study the signals from these detectors with sources and electron beams from the TTU Van de Graaff accelerator (February - April 2006)
• Study techniques to separate scintillation and Čerenkov signals from these detectors in the TTU lab environment (February - April 2006)
• Build full size em calorimeter based on selected technology (May - July 2006)
• Test this detector at the CERN SPS with high-energy electron and hadron beams (August 2006)

Deliverables: A homogeneous dual-readout electromagnetic calorimeter, as well as test results obtained with this instrument.

FY2007 Project Activities and Deliverables

We plan a combined electromagnetic and hadronic prototype test at the CERN SPS. The new em calorimeter followed by the existing DREAM hadron calorimeter, possibly equipped with three different types of fibers, will be exposed to beams of electrons, hadrons and “jets” (secondaries from interactions in an upstream target). The viability of the dual-, and possibly triple-readout techniques for improving hadronic performance will be tested.

Budget justification: Texas Tech University

The requested budget only concerns work on the em section, and is thus significantly lower than in the original proposal. Depending on the funding situation and on progress made elsewhere in the development of SiPMs, we may decide to revise our FY2007 request later on.

Texas Tech University will be the lead institution in this project. In order to reduce paperwork and complexity, no subcontracts will be used. Travel for our UCSD and ISU collaborators will be handled by TTU, which charges no overhead on travel.

Equipment, materials and supplies, and travel dominate the cost of this project.
We are using professional expert assistance (colleagues in our chemistry department, as well as outside consultants) in scintillator dopants and doping techniques. Undergraduate students are involved in the (preparations for the) tests planned for next year. The fringe benefits rate is assumed to be 25% on salaries.

There will be no overhead charged on equipment and travel. TTU will charge overhead on salaries, materials and supplies at the off-campus rate (26%).

Two-year budget, in then-year K$

**Institution:** Texas Tech University

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6.18: Development of a New Concept Detector [also includes vertex, tracking and muon systems]

(new proposal)

Calorimetry

Contact person
John Hauptman
hauptman@iastate.edu
(515) 294-8572

Institution(s)
Iowa State
Lecce (Italy)
IFIN-HH Bucharest

New funds requested
FY06 request: 39,300
FY07 request: 39,900
Development of a New Concept Detector

**Classification** Muon and Calorimeter

**Personnel and Institution requesting funding** John Hauptman

*Iowa State University, Ames, IA 50011*

Collaborating personnel who will work on the project but are not requesting funding here.

Emanuela Cavallo, Vito Di Benedetto, Anna Mazzacane

*Università degli Studi di Lecce, Lecce, Italy*

Sehwook Lee, Matt Stemper

*Iowa State University, Ames, IA 50011*

Sorina Popescu, Laura Radulescu

*IFIN-HH, Bucharest, Romania*

**Project Leader**

John Hauptman

hauptman@iastate.edu

515-451-0034

**Project Overview**

We are developing a complete and new concept detector consisting of four major subsystems: a pixel vertex detector, a single-electron sensitive TPC, a triple-readout fiber calorimeter, and a dual-solenoid muon system. The pixel and TPC developments are the work of other groups working on the ILC (mainly GLD and LDC groups, and the tracking-TPC groups), whereas the calorimeter and muon detector systems are completely new to high energy physics and their successful design and development are critical to the 4th Concept detector.

The triple-readout calorimeter measures three components of every hadronic shower: the finely spatially sampled scintillation light generated by \(dE/dx\) of all charged particles, the Čerenkov light generated primarily by electrons, and the MeV neutron content correlated with binding energy (BE) losses. These multiply redundant measurements result in exceptional hadronic energy resolution by virtue of event-by-event measurements of all the main fluctuations in hadronic showers: spatial, EM fraction, and binding energy (BE) losses.

The dual-solenoid for the muon system is also new in high energy physics and consists of an inner tracking solenoid to establish the TPC field, and an outer solenoid that returns the flux through the annulus between the solenoids. This geometry accomplishes many objectives: (i) muons are measured in an air volume with a momentum resolution of \(\sigma_p/p^2 \sim 3 \times 10^{-4}\) (GeV/c)^{-1}; (ii) the physics acceptance for muons is greatly increased at low momenta down to 2-3 GeV/c; (iii) positive identification of muons (especially in conjunction with the triple-readout calorimeter) is enhanced; and, (iv) the cost is reduced over a conventional Fe-chamber sandwich muon system.

The main theme of the 4th Concept is multiply redundant and integrated measurements of all the bosons and fermions of the standard model.
Broader Impact
The work on this project is directed from within a single-investigator group of a university professor and students, mainly undergraduate physics majors, working on a new problem and seeking new solutions. This explicitly integrates teaching and research since our students have office space in our lab area in the Physics Department. It is a place where they can also do their problem sets.

More funds for undergraduate and beginning graduate students will allow us to hire more students. At this stage of work, several problems are available that are person-intensive, rather than equipment-costly: GEANT4 code for the explicitly detailed simulation of the triple-readout fibers, incorporation of the dual-solenoid into GEANT4 and analysis of the muon system capabilities; and above all, the development of "IVCRoot", the Lecce group's work on a comprehensive 4th concept simulation and physics analysis structure. All of these activities are perfect for physics majors and beginning graduate students, and as we know, these are the best recruitment tools available in physics. At Iowa State, one undergraduate (Matt Spemper) and one graduate student (Sehwook Lee) are working on this, and at Lecce three physics students (Anna Mazzacane, Emanuela Cavallo and Vito Di Benedetto) are working full time. At ISU, I have managed to keep individual students for 1-4 years (e.g., Shauna Dennis and Sam Ose) before they naturally go on.

The achievement of broad impact to enhance scientific and technological understanding and potential benefits to society at large is obtained, in these small high energy physics groups, by sending students out into the world to workshops and conferences. Already Sehwook Lee attended our 4th meeting at Fermilab, along with graduate student Efe Yazgan and postdoc John Strologas. It is the intent of this small request to be able to support these students.

Results of Prior Research
The calorimeter has substantial beam testing at CERN resulting in five publications in Nucl. Instr. Methods:


This calorimeter is thoroughly well understood. The level of detail and understanding is beyond what I am used to in other detectors: TPC calorimeters (Berkeley/SLAC), LArgon (SDC), scintillator tile (SDC), HPC (Delphi/LEP), and others.

Current and future work will center on the question of measuring the neutrons in a hadron shower, by several possible means outlined in our detector description, and the calculations and simulations for making a judgment about which method to choose.
The dual-solenoid is being calculated and simulated. This work is ideal for an undergraduate physics major (say, at ISU) coupled with a graduate student at Lecce (Emanuela Cavallo), in addition to the work done by me and Robert Wands with ANSYS at Fermilab. This work is well underway, but requires the solution of physics problems involving the measurement of muons.

Progress to date includes a detector description, several talks at Linear Collider meetings (Paris 2004, SLAC 2004, Snowmass 2005, and Vienna 2005), the development of a team of people who work on the 4th concept, and the development of a full first-principles simulation of the whole detector.

Documents describing work accomplished, all of which are accessible at the website http://high-energy.physics.iastate.edu/ilc, are

5. "Description of the Fourth Concept Detector (4th) for the International Linear Collider", Cavallo, it et al., version 0.2, November 2005.
6. "Dual Readout Calorimetry for the ILC", LCRD proposal, Jan. 2005

In addition, a full set of papers and figures of all aspects of the dual-readout calorimeter test is at the website http://www.phys.ttu.edu/dream.

Facilities, Equipment and Other Resources

The work is taking place in Lecce, Ames (ISU), Bucharest (IFIN-HH), Lubbock (TTU), Albuquerque (UMN), and Fermilab. These places have sufficient resources to support this design work, and we not request facilities support.

FY2006 Project Activities and Deliverables

The main deliverable is a Detector Outline document for the LCWS06 Bangalore workshop in March 2006. This will include a full calorimeter simulation, an full understanding of the capabilities of the dual-solenoid for a muon system, and an analysis of the final state in

\[ e^+e^- \rightarrow HZ \rightarrow (H \rightarrow X) + e^+e^-, \mu^+\mu^-, \text{and} jj \]

and possibly an analysis of a precision measurement of the t quark mass.

FY2007 Project Activities and Deliverables

The second year will see the design and initial prototype construction of important aspects of a triple-readout calorimeter. This involves a tungsten (W) absorber, three kinds of fibers, a time-history readout of the scintillating and Čerenkov fibers, and a photoconverter selection. Separate funding has been requested for the beam test module itself, and here we only request support for design and testing.
FY2008 Project Activities and Deliverables

The third year will include the beam testing of the triple-readout module and its analysis, and the final definition of the 4th Concept detector for the ILC.

Budget justification: Iowa State University

All funds requested are for the support of people, mostly students, working on the design, physics, simulation and understanding of the 4th Concept detector. We do not request funds for senior personnel, other than travel funds to LCWS meetings, and where possible we will include students on these trips.

Three-year budget, in then-year K$

Institution: Iowa State University

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6.19: Calorimeter and Muon ID

(new proposal)

Calorimetry

Contact person
A.J.S. Smith
smithajs@princeton.edu
(609) 258-5590

Institution(s)
IHEP Beijing
Princeton

New funds requested
FY06 request: 60,216
FY07 request: 60,051
ILC Detector R&D Proposal:  
Calorimeter and Muon ID

Hadron Calorimetry and Muon Detection at the ILC, using the BESIII type of Resistive Plate Chamber as the active detector element.

Changguo Lu, Peter D. Meyers, James D. Olsen, William Sands, A. J. S. Smith, Jed Biesiada (graduate student), and one undergraduate student

Princeton University

Collaborators
Yifang Wang, Associate Director of IHEP; Jiawen Zhang, group leader of BESIII Muon detector, IHEP, Beijing. Collaborating personnel will work on the project but are not requesting funding.

Project Leader
Name: A. J. S. Smith
Email: smithajs@princeton.edu
Phone: 609-258-5590

Project Overview

1. Introduction. All proposed detector concepts for International Linear Collider experiments require a hadron calorimeter and muon identification. Each of these two subsystems must have detectors with the following common features:
   — large area
   — low cost
   — suitability for industrial mass production
   — high efficiency under actual hit rates
   — longevity

So far two major technologies have been brought forward for such applications: RPC’s of various types, and plastic scintillator strips. Mainly because of their lower cost, RPC’s have been adopted by several large colliding-beam detectors, and have been operating for many years with mixed success. An extensive R&D program has been underway in many experiments, including BaBar, ATLAS, and CMS, to understand and correct various problems and weaknesses that showed up under high-rate operation.

Recently a new type of RPC has been developed for BESIII that appears to be a major improvement, making it a promising candidate detector for ILC hadron calorimetry
and muon ID. However, many properties must still be researched and characterized before one can be sure it will meet the many demanding requirements for successful long-term operation under ILC conditions.

2. RPC use in major HEP Experiments. The following table gives a brief survey of large RPC systems in present and future experiments:

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The failure of the BaBar RPC’s in summer 1999 prompted the international RPC community to devote tremendous effort on aging studies, and mainly due to the LHC RPC R&D work, we now have much better understanding for the mechanism of RPC operation, aging, rate capability, etc. It has been clearly shown that RPC performance and degradation are determined by complex interactions among the operating conditions and the materials of the RPC’s, in which the current, integrated charge, humidity, production of hydrofluoric acid, etc. affect the linseed oil, graphite coating, and the bakelite itself, in complex ways that result in degraded performance (increased dark current, reduced efficiency, increased resistivity, “death” by migration of graphite, etc.) In some ways glass RPC’s are more robust, but the high resistivities of inexpensive glasses make them unsuitable for high-rate operation.

We shall continue to investigate and characterize these mechanisms as part of our proposed R&D project, comparing “conventional” and “new” RPC’s, with the goal of designing an optimal RPC configuration for the ILC. The following sections will explain all this in more detail.

3. The BESIII RPC concept and performance. Linseed oil coating, a dominant feature of bakelite RPC technology, has brought both advantages and serious problems. The performance of Bakelite RPC’s with and without a linseed oil coating differs greatly,
as can be seen in Fig. 1 and Fig. 2\(^1\), which demonstrate that the dark current and singles rate for an oiled RPC are two orders of magnitude less than for a non-oiled chamber; it is therefore not surprising that most large RPC systems used oiled bakelite surfaces. However, the aging problems of oiled surfaces prompted the IHEP group to take another look at non-oiled bakelite, with great result.

So far the BESIII group has fabricated \(~1000\) RPCs with non-oiled bakelite of extremely high surface quality. The average area for the endcap RPC’s is \(1.3 \text{m}^2\), for the barrel, \(1.4 \text{m}^2\). The largest RPC they can make with their present capability is \(1.2 \text{m} \times 2.4 \text{m}\). The performance of 444 barrel RPCs is summarized in figure 3. The dark currents, efficiencies, and singles rates of this sample are comparable to those of oil-coated Bakelite RPC’s, at least for short term operation at low rates.

---

\(^1\) M. Abbrescia et al. NIM A394(1997)13, Effect of the linseed oil surface treatment on the performance of resistive plate chambers.
4. **Test results on BESIII RPC’s at Princeton.** We have obtained a prototype RPC from BESIII (50×50cm² in area) and performed various tests on it. Measurements of dark current and singles rate plateau confirm the BES results, and indicate steady improvement during high voltage training over several weeks. Figure 4 shows the test results. After a month of training the dark current is approaching 0.5µA/m² and the singles rate curve starts to show a plateau with HV. The counting rate in the plateau region, ~0.075/cm², is only ~3 times of the cosmic ray background, approximately the same as for top-quality linseed-oiled bakelite RPC’s.

![Figure 4](image)

**Figure 4.** The evolution of the dark current and single’s rate plateau during the high voltage training for a BESIII RPC prototype.

The excellent performance of the prototype led us to begin serious R&D work to understand this superiority over the ordinary Bakelite RPC. First, we have taken surface morphological images of the BESIII Bakelite and BaBar Bakelite with an Atomic Force Microscope. The images in Figure 5 show the BES bakelite to be significantly smoother. (Note differences in vertical scale as given in the figure caption)

![Figure 5](image)

**Figure 5.** Bakelit surface morphological images: (A)(B) BaBar sample, (C)(D) BESIII sample. Note the vertical scale difference: (A) 996nm, (B) 783nm, (C) 264nm, (D) 528nm.
5. Analysis of Test Results. The feature structure of the defects on the surface as we can see from figure 5 may be categorized into the four types shown in Fig. 6: “pin,” “ball,” “dome,” and “ridge.” We have used finite element analysis software ANSYS to calculate the electric field variation due to these defects. The tips of “pin” and “ridge” have been rounded to $R = 0.5 \mu m$, and the height is the distance from the base to the tip (before being rounded).

Figure 6. Illustration of the parameters of the surface defects used in the Finite Element Analysis calculation.

The FEA results, shown in Table 2, show that the most serious defect type is the “pin”. Hence one can conclude that the linseed oil coating plays an important role in covering this kind of surface defect, thereby avoiding regions of excessive electric field on the electrode, and preventing field emission, a likely source of high dark current and high singles rates.

Table 2. Maximum electric field at the defect, for $V = 1000V$ in a gap of width 2mm.

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<th>Height (mm)</th>
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<th>“ball”</th>
<th>“dome”</th>
<th>“ridge”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base (mm)</td>
<td>0.02</td>
<td>0.008</td>
<td>0.002</td>
<td>0.1</td>
</tr>
<tr>
<td>Emax (MV/m)</td>
<td>60</td>
<td>14</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>
6. Proposed R&D program at Princeton and IHEP. Our results so far are highly promising, and indicate that oil-free RPC's could be an attractive candidate for hadron calorimetry and muon ID at the ILC. However, many more tests must be done before this technology can be considered sufficiently robust and stable to trust in an ILC detector, which must operate with high performance for many years. In particular, a recent report describes intensive studies and presents new insights\(^2\) on several serious aging issues in conventional RPC's. The BESIII RPC’s have not yet been subjected to these absolutely crucial tests; our R&D proposal is therefore aimed at studying these issues and others for the BESIII RPC’s under ILC conditions. We are also confident the results of this work will be of interest to the international RPC community.

a. Hydrofluoric acid damage to Bakelite surfaces. Hydrofluoric acid (HF) is produced in the RPC gas by the decomposition, under electrical discharge, of tetrafluoroethane, C\(_2\)H\(_2\)F\(_4\), the main component of most RPC gas mixtures. This very aggressive acid is expected to have a main role in damaging the RPC inner surface. This issue has been studied in detail by Santonico et. al \(^2\), in experiments where the significant concentration of HF in the exhaust gas from RPC’s was trapped by bubbling the gas in water where the fluorine is detectable as F- ions. The output gas was bubbled through a liquid mixture known as Total Ionic Strength Adjusting Buffer (TISAB), optimized to perform accurate F- measurements with electrode probes. The apparatus is shown in Fig. 7. The F- ions contained in the exhaust gas were trapped by the TISAB and the resulting concentration of F- ions was measured by an electrode probe immersed in the TISAB and connected to an acquisition system which monitored on line the probe output voltage. During the entire test, which lasted usually several hours, the fluorine produced inside the chamber was continuously transferred to the TISAB and the increase of the F- ions concentration was measured on line. In figure 8

they show the amount of $F^-$ ions trapped by the TISAB vs. time for two different i-C4H10 concentrations, 5% and 30%, and the same working current of 15 mA. The slopes of the curves represent the rate at which $F^-$ ions are generated.

We plan to conduct similar measurements with the BESIII RPC’s. In addition, and perhaps most important, we shall determine as quantitatively as possible the correlation between fluorine concentration and damage from aging.

Figure 8. $F^-$ ions gathered vs. time for two different isobutane concentrations: 5% and 30%. The operating current kept constant at about 15 $\mu$A in both cases.

b. Bakelite Resistivity Studies. Experience has shown that long-term operation of RPC’s at high rates results in a gradual increase in resistivity of the plates, which has the consequence of decreasing the RPC’s rate capability. This is due to at least two effects – drying of the bakelite, and reduction of the thickness of the graphite coating. The evolution of the electrode plate resistivity vs. the aging time in the course of about 15 months irradiation at X5-GIF, is shown in Fig. 9 for six ATLAS standard production RPCs3. The integrated charge per unit surface and the gas relative humidity are also reported in the figure. The gas humidity was set at controlled values during the test. In the last 5 months of test, as is also indicated in Fig. 9, the external environment was humidified at about 50% relative humidity. The operation at low gas humidity during most of the first 11 months of test produced a gradual increase of the resistivity that is mainly related to the integrated charge. It was found that when the relative humidity is increased

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at about 50% both in the working gas and in the environment, the resistivity starts decreasing back towards its initial value. This test suggests that the free charge carriers responsible for the conduction in the plastic material are produced by water electrolysis: the current across the plates removes the charge carriers and produces the observed increase of resistivity if these are not replaced by new ones. This mechanism of electrical conduction can be studied in the laboratory using small size samples of laminate that are kept under large currents. It should be stressed that a satisfactory understanding of the electrical conduction in all kind of materials used as RPC electrode plates, still remains a central task for the RPC scientific community. This issue also needs careful study on the BESIII electrode.

Another serious aging effect is the diminishing of the graphite coating after flowing certain amount of charge through the chamber. BaBar has observed such effect\(^4\). The present limit for this effect to take place is \(-0.3 \text{ C/cm}^2\)\(^5\). It might depend upon the graphite coating technique; also may related to the electrode material, therefore the test for BESIII RPC is also required.

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c. **Detailed morphological studies for BESIII Bakelite.** At this time ours is the only data on the morphology of Bakelite surfaces, and only a very limited set of samples have been tested. We plan to assemble a comprehensive set of samples and scan them under our atomic force microscope. Once this data has been analysed we shall then study the effect of various surface treatments on the surface smoothness. As appropriate we may also study other types of bakelite.

d. **Rate capability of the BESIII RPC.** To meet the various rate requirements of the real experiments it is advantageous to be able to specify the optimal resistivity of the RPC electrodes. Bakelite is very attractive in this regard because the manufacturing process can produce plates of well-determined resistivity over the range of interest in this important parameter. To determine the optimum, we shall build a series of RPC prototypes with different Bakelite resistivities, and then test their efficiencies vs. background hit rate. This test will be done at IHEP, Beijing, where we can use a strong gamma source, and also use the electron test beam line to check the efficiency.

e. **Overall aging performance of BESIII RPC.** We have listed various works on the RPC aging performed so far in the world RPC community, most of which were done on a very special category of RPC based on Italian Bakelite electrodes. Since many of the materials in the BESIII type differ greatly, it is critical to perform new independent, thorough aging studies on the BESIII configuration. In fact this direct aging test is a major final criterion by which to judge the chamber.

We shall use the same setup used in the rate-capability tests to perform overall aging tests. Specifically, the test RPC’s, while at full high voltage, will be radiated for long periods by a strong gamma source. The current will be recorded and integrated to measure the total accumulated charge, and the chamber efficiency will be measured periodically in the IHEP beam line.

**Facilities, Equipment and Other Resources**

1. **Princeton HEP group Facilities and Equipment.**
   a. **General.** The Princeton Elementary Particles Laboratory provides a comprehensive suite of mechanical and electronics fabrication and test facilities, including a large class-100 cleanroom; electronics fabrication and test equipment; modern CAD systems, FEA analysis capabilities, and software for circuit and chip design; CNC and NC machining centers, lathes, and mills; 3000 sq-ft fabrication area covered by a 2-ton crane.
   b. **Specific to RPC R&D.** Princeton has been involved in the BaBar RPC improvement project for 6 years, and have accumulated a significant amount of dedicated equipment for our studies, such as a CAMAC system, 10kV high voltage supplies, mass flow control systems, a LabVIEW data acquisition system, etc.
c. *Princeton University Facilities.* We are very fortunate to have access to world-class imaging and materials-testing facilities in our Engineering School, specifically those housed in the Princeton Institute for the Science and Technology of Materials (PRISM). These have been, and remain essential to our studies of surface morphology, and to various diagnostics on the RPC materials as they age.

d. *Recent R&D experience.* Beginning in February ‘05 our R&D has focused on the feasibility of switching over the second-generation BaBar endcap RPC’s from streamer to avalanche (proportional) mode; the project is of utmost importance as without such intervention the inner regions of many layers would suffer serious aging and loss of efficiency under the high-rate conditions of operation at $>10^{34}$ luminosity. The main challenge, of course, is that neither the detector, gas mixture, power supplies, signal transmission lines, nor the electronics had been designed to deal with the tiny signals produced and other implications of avalanche mode operation. Fortunately, our project has been highly successful, and we are already taking data with 3 of the highest rate layers in avalanche mode. The rest will be switched over within the next few months. This work, all done at Princeton, is not only directly relevant to the research of this proposal, but has given us the added benefit that our test facility is up-and-running.

e. *Beijing Facilities and Resources.* The good link between Princeton and IHEP, Beijing, is essential for this project. The IHEP scientists, who developed the Bakelite surfaces, and are very interested in working with us to produce an RPC system suitable for the ILC. Furthermore, IHEP’s strong radioactive sources and test beam lines are very critical resources for the aging test. We also point out that a Princeton-IHEP collaboration is particularly natural because Changguo Lu had worked there from 1982 to 1989 as the group leader of the shower-counter system for the BES barrel.

**FY2006 Project Activities and Deliverables**

In the first year of the project we plan to concentrate on aging studies for several prototypes.

1. Aging tests will be performed in summer 2006 at IHEP, Beijing, at their CO-60 source and test beam line.

2. In preparation for these tests we shall build several new prototypes at IHEP and Princeton.

3. Lu and an undergraduate student will work on new morphological studies at Princeton on RPC’s with various surface treatments, and confirm our present appraisal of the BESIII Bakelite electrode.

4. A fluoride test station and gas analysis system will be set up at Princeton this spring to analyze the production and effects of fluoride ions. Results will be reported either at the end of FY 06 or early in FY 07.
FY2007 Project Activities and Deliverables

The main tasks and deliverables for FY 2007 are:

1. Based on results from the above FY 2006 R&D, design and build full-size RPCs with various electrode resistivities.

2. Use the IHEP test beam to study the rate capability and optimize the readout configuration.

3. Prepare a design report for a reliable, cheap RPC system for hadron calorimetry and muon ID at the ILC.

Budget justification: Princeton University

1. Personnel costs. We require support for one technician-month/year for making parts, etc. We also need to hire a undergraduate student for three months to participate the Bakelite morphological study in the first year and data taking for RPC testing in the second year. We also request summer support for one graduate student in FY 2006 and FY 2007. Engineering and additional technical support will be provided from the Princeton base program as needed.

2. Apparatus. As described above, a large fraction of the necessary apparatus is already in hand from previous R&D. However, we need the following items to complete the system.

   a. Gas Chromatograph system, and fluoride ion detection system. During the SSC era we assembled a very good mass-flow controller system, but it still leaves uncertainties in the absolute final mixing ratio. Adding a GC system is needed to reduce these uncertainties to the levels required for definitive results. It is also good for training the students who want to do experimental work in our lab.

   b. Electronics. We possess very small amounts of modern electronics, but have to rely too much on items more than 15 years old (they were granted to us for SCC R&D). It is still useful for the non-critical parts of the system, for which we plan to deploy it. We shall implement the modern ADC’s, linear fan-in/out’s, and low-level discriminators requested for the most sensitive measurements.

   c. Fluoride-ion probe.
### Requested Apparatus (As much in FY 2006 as possible)

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<th>Item</th>
<th>Use of the item</th>
<th>Qty</th>
<th>Unit price</th>
<th>Total cost</th>
</tr>
</thead>
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<td>Analyze gas for gas mix</td>
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<td>$15,000</td>
<td>$15,000</td>
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<tr>
<td>CAMAC ADC (peak sensitive) 16 channels</td>
<td>Record signal peak amplitude</td>
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<td>$3,225</td>
<td>$6,450</td>
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<tr>
<td>NIM Linear fan-in/fan-out, 16 channels</td>
<td>Split the analog signal to multiple outputs</td>
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<td>$925</td>
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<td>Low threshold discriminator, 16 ch.</td>
<td></td>
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<td>$5,800</td>
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<tr>
<td>Fluoride probe</td>
<td>Analyze the fluoride ions in the gas mix</td>
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<td>$500</td>
<td>$1,000</td>
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$31,950

### Two-year budget, in then-year K$

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<td>Undergraduate Student (2 mo/yr)</td>
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<td>3.650</td>
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<td>15.441</td>
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<td>Total direct and indirect costs</td>
<td>60.216</td>
<td>60.051</td>
<td>120.267</td>
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</table>
6.20: A Calorimeter based on Scintillator and Cherenkov Radiator Plates Readout by SiPMs

(new proposal)

Calorimetry

Contact person
Tianchi Zhao
tianchi@u.washington.edu
(206) 543-936

Institution(s)
Washington

New funds requested
FY06 request: 90,503
FY07 request: 93,008
A Calorimeter Based on Scintillator and Cherenkov Radiator Plates Readout by SiPMs

(New Proposal)

Calorimetry

Contact person
Tianchi Zhao
University of Washington
tianchi@u.washington.edu
(206) 543-9136

Institutions
University of Washington
Fermilab

Funds requested
FY06: $90,503
FY07: $93,008
A Calorimeter based on Scintillator and Cherenkov Radiator Plates Readout by SiPMs

Classification (subsystem)
Calorimeter

Personnel and Institution(s) requesting funding
University of Washington: Tianchi Zhao

Collaborators
Adam Para
CD-Computer & Engineering for Physics
Fermi National Accelerator Lab
para@fnal.gov
(630) 840-2132

Contact person
Tianchi Zhao
University of Washington
tianchi@u.washington.edu
(206) 543-9136
Project Overview

We propose to study the design of a calorimeter for the ILC experiment constructed by using plastic scintillator and Cherenkov radiator plates to achieve compensation based on the dual readout principle. We also will investigating the possibility of using the Cherenkov light observed in hadron jets to help separate the neutron components and the charged hadron components that is an essential requirement in the content of the particle flow algorithm (PFA) for jet energy reconstruction. Both the plastic scintillator plates and the Cherenkov radiator plates will be readout by using imbedded WLS fibers and SiPM [1] mounted directly on the plates. We believe with sufficient R&D effort, a design of a compact and fully compensated calorimeter with an EM energy resolution less than \(10%/\sqrt{E}\) and a jet energy resolution \((20-30\%)/\sqrt{E}\) plus a constant term of \(~1\%\) can be developed.

The concept of using Cherenkov radiation to achieve compensation in a homogeneous hadron calorimeter was first studied using computer simulation method by D.R. Winn and W.A. Worstell [2] and in 2003, a proposal titled “Cherenkov compensated calorimetry” lead by Yasar Onel of University of Iowa was submitted to the LCRD program [3] for further studying this method. Studied by another group lead by Richard Wigmans using quartz fiber and scintillating fibers imbedded in copper have shown very promising results [4] based on this dual readout concept. Although sharing some common design principles, the configuration of our proposed calorimeter are quite different from the one described in ref. [4].

The calorimeter configuration that we are proposing will have several advantages. Its main advantage is the possibility of achieving compensation by exploring the dual readout technique. The hadron cluster shape defined by the Chrenkov radiation will be narrow that may help the separation for charged and neutron hadron clusters in the PFA scheme. The fine segmentations both in the transverse and longitudinal direction will allow the identification of electromagnetic and hadron showers. This design also will be better adapted to the environment of a collider detector.

1. Introduction

Jet detection with good energy resolution is fundamentally important for physics and also is one of the most challenging tasks at the International Linear Collider with the central of mass energy at 1 TeV. The three main detector concepts at ILC are investigating different approaches in order to meet the very challenging requirements. The GLD concept has chosen a calorimeter baseline that uses plastic scintillator plates as active media and tungsten/lead plates as passive absorbers. Several different technologies are been investigated by LDC and SiD detector concepts. In the DHCal design, the technologies used in EM section and the Hadron section are completely different. One of the EM calorimeter choices is highly segmented silicon pad detectors with thin tungsten absorber plates. The hadron section is based on binary readout with very small (1 cm²) detector cells. The total readout channels for the EM and hadron calorimeters combined can exceed 100 million in this design. These calorimeter design concepts rely on the Particle Flow Algorithm (PFA) to achieve the required jet energy resolution. The calorimeter depths (EM plus hadron) for the 3 main detector concepts are about 1.5 meters and have 5 to 6 interaction lengths. The absorber materials being considered are tungsten, lead or steel.
We propose to study a different design of a calorimeter constructed by using plastic scintillator plates, Cherenkov radiator plates and structural material. In addition to the plastic scintillator plates used as active detectors in the GLD concept, we propose to study the possibility of partially or completely replacing the passive absorber plates by Cherenkov radiator plates. The preferred Cherenkov radiator material will be high density lead glass. Heavy metal sheets can be inserted if we need to make the calorimeter more compact. The calorimeter will have both transverse and longitudinal segmentations that can be similar to that used in the GLD concept. Both the scintillator and Cherenkov radiator plates are readout by the new silicon photomultipliers.

The basic principle of achieving compensation in our proposal is the same as the one studied earlier and discussed in ref. [2],[3],[4]. As shown in Fig. 1, the calorimeter design of ref. [4] is based on the spaghetti calorimeter geometry with two types of fibers, the scintillating fibers and quartz fibers imbedded in copper absorber. The scintillating fibers are sensitive to both hadronic and EM components of the hadron showers and the quartz fibers are mostly sensitive to EM components. The large bundles of two different types fibers are separated at the outside end of the calorimeter and are routed to large photomultipliers. The compensation can be achieved on an event-by-event based on the two independent energy measurements by properly adjusting the relative energy scale between the EM and the hadronic components of the jets. In such a design, fibers are laid in the radial direction and run the full depth of the calorimeter without longitudinal segmentation. The energy response has an angular dependence and discriminating EM and hadron showers can be difficult especially for high energy jets in which many particles are densely packed together without knowing the depth of shower development from the longitudinal segmentations.

![Image](image_url)

Fig. 1. The basic configuration of the DREAM calorimeter discussed in ref. [4].

2. Proposed detector configuration

Our proposed detector configuration is quite different from the DREAM calorimeter described above. The basic configuration of the calorimeter is shown in Fig. 2. Optimum segmentations and choices for active detector and passive absorber materials will be the subjects for the R&D program. Here, we provide some general discussions.
The behavior and energy resolution of calorimeters constructed from scintillator plates readout by SiPM and passive absorbers have been studies extensively. Results of these studies can be used as a guide when we conduct our design studies. We will concentrate our effort on the Cherenkov detectors and their effects on compensation based on the dual readout scheme.

The properties of some common Cherenkov radiators are given in the Table 1. Lead glass is a common Cherenkov radiator that has been used in the electromagnetic calorimeters extensively in the past. Lead glass with PbO content as high as 80% with density as high as 6.2 g/cm³ is commercially available. Such kind of lead glass will be an ideal Cherenkov radiator material for our design. Both the radiation length and the hadronic interaction lengths are reasonably short allowing us to design a very compact calorimeter. We expect only the first ~3 interaction lengths of the calorimeter are important for achieving compensation. Therefore after 3 radiation lengths, the dual readout will likely not be necessary and the lead glass can be replaced by regular heavy absorbers. The total volume of Cherenkov radiator required will be on the order of 100 m³.

Table 1. Properties of Cherenkov radiators.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Refractive Index (n)</th>
<th>Nuclear Interaction Length (cm)</th>
</tr>
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<tbody>
<tr>
<td>Lucite</td>
<td>1.18</td>
<td>1.47</td>
<td>~70</td>
</tr>
<tr>
<td>Non-Leaded Cover Glass</td>
<td>2.5</td>
<td>1.52</td>
<td>~40</td>
</tr>
<tr>
<td>Medium-density lead glass</td>
<td>3.2 - 3.7</td>
<td>1.59</td>
<td>~25</td>
</tr>
<tr>
<td>Medium-density lead glass</td>
<td>4.2</td>
<td>1.70</td>
<td>~25</td>
</tr>
<tr>
<td>High-density lead glass</td>
<td>5.2 - 6.2</td>
<td>1.81-1.9</td>
<td>~25</td>
</tr>
</tbody>
</table>

The calorimeter will need to be divided into two sections, the EM section and the hadronic section. In general, segmentations in the EM section need to be finer than the segmentations in the hadron section. In principle, both can be constructed using the same Cherenkov and scintillation radiator sandwiched structure with somewhat different geometric parameters. We assume the thickness of lead glass plates is 2.5 cm for the hadron section in the following discussions.

The calorimeter configuration discussed above can also be used as hadron calorimeter only and the tungsten silicon or tungsten scintillator EM calorimeters can be placed in front of it. The EM calorimeter typically is about one interaction thick and a significant fraction of hadrons will
interact in it. Therefore, the EM calorimeter must also be able to compensate its different response to EM and hadron showers.

The Cherenkov radiator can also be made from Lucite in conjunction with high z metal such as tungsten and uranium. The Cherenkov light yield in Lucite will be about 50% lower compared to the light yield in high quality lead glass because lower refraction of index and the spectrum response. With a much smaller sampling frequency, we expect the performance of the detector will be degraded somewhat if we choose this approach.

3. Cherenkov light yield

The yield of the Cherenkov light when a charged particle penetrates a piece of radiator is determined by the index of refraction of the radiator and the velocity $\beta$ of the particle. The photon absorption in the radiator also plays a critical role. The Cherenkov photon yield as functions of $\beta$ and the index of refraction in the wavelength range of 400 to 700 nm is shown in Fig. 3. For materials listed in Table 1, the light yield is 260 to 350 photons per centimeter or 650 to 875 photons for a 2.5 cm thick radiator plate if $\beta$ approaches one.

![Fig. 3. Cherenkov light yield as a function of particle velocity and the index of refraction of the radiator.](image)

The Cherenkov threshold $\beta_{th}$ is given by

$$\beta_{th} = \frac{1}{n}$$

where $n$ is the index of refraction of the radiator. As the Fig. 3 shows, the Cherenkov light yield increases with the particle velocity $\beta$ and reaches a maximum when $\beta$ approaches one.

4. Exploring the Cherenkov light

We plan to study two main effects of the Cherenkov light in the calorimeter.
(1) Compensation

Within showers produced by hadron jets, the Cherenkov light is mostly produced by the EM components of hadron showers. This is because the majority of electrons and positrons produced in showers mostly have $\beta$ value very close to unity, whereas the majority of the hadrons produced in hadron showers have $\beta$ value much less than one. Also, the total number of charged particles in a hadron shower with $\beta > \beta_{th}$ is much large in EM showers than in the hadron showers of similar energy. The calorimeter compensation will be based on these phenomena. We need to study these effects in detail to find the best and the most economical detector configuration.

(2) Shower shape and separation

Because the hadron interaction length is much larger than the radiation length in detector medias, an EM shower is concentrated in a much smaller volume compared to hadron showers that will have a much larger spatial spread. The charged particles that are capable of emitting Cherenkov light tend to be concentrated in the forward direction. The shower shape defined by the Cherenkov light in a Cherenkov radiator based calorimeter will be more compact that the shape defined by a scintillating lights in a scintillator based calorimeter. The configuration of the calorimeter that we are proposing can take advantage of these phenomena.

In a calorimeter based on the PFA algorithm, separating the neutron clusters from the charged hadron cluster is very difficult because particle showers in the high energy hadron jets tend to overlap in the calorimeter. The fact that the showers measured from the Cherenkov light are much more compact can be used to help separating energy clusters caused by neutral and charged hadrons. Monte Carlo studies are needed in order to verify this speculation.

5. Cherenkov light readout

Both the plastic scintillator plates and the Cherenkov radiator plates are readout by using imbedded WLS fibers and SiPMs that are directly mounted on the plates in a similar fashion as used in other scintillator plate based calorimeters. A basic readout configuration is shown in Fig. 4 as an example.

![Fig. 4. WLS fiber readout for a scintillator plate with a SiPM mounted at the lower right corner. This photo was taken by the CALICE collaboration.](image-url)
Here, we only discuss the Cherenkov light readout. Since the Cherenkov light yield is much lower than the scintillating light yield in plastic scintillators, maximizing the light collection efficiency is more important in order to collect sufficient amount of photoelectrons.

(1). Cherenkov light collection using WLS fiber

The photoelectron yield from Cherenkov light in a piece of lead glass readout by WLS fiber was studied at DESY for the design of the TESLA forward calorimeter [5]. As shown in Fig. 5, the lead glass strip used in this study has a cross-section 10 mm x 10 mm and the length is 4 cm. A 1 mm diameter WLS fiber was imbedded in a groove on the top surface of the lead glass strip. The lead glass was SF57 flint glass with an index of refraction ~1.8. The WLS fiber was readout by a XP1911 PMT with an estimated average quantum efficiency of 15 ± 2%. The number of photoelectrons observed by the PMT were measured by using spectrum hardened cosmic ray muons and the result obtained was 2.4 ± 0.5 photoelectrons per muon.

Fig 5. Lead glass strip with a imbedded WLS fiber.

Once the number of Cherenkov photons (N\textsubscript{\gamma}) produced is known in a radiator block, the number of photoelectrons (PE) observed by a photon detector attached to one end of a WLS fiber imbedded in the Cherenkov radiator can be estimated by

\[ \text{PE} = N_{\gamma} \eta_1 \eta_2 \eta_3 \eta_4 \]

\( \eta_1 \): the probability of a photon hits the WLS fiber
\( \eta_2 \): the quantum efficiency of the WLS fiber
\( \eta_3 \): the light “trapping” efficiency of the WLS fiber
\( \eta_4 \): the quantum efficiency of the photon detector

The light collection efficiency of the WLS fiber \( \eta_1 \) can be enhanced by the multiple reflections of photons on the surface of the radiator block and can be much larger than the fraction of the aerial coverage by the WLS fiber. The quantum efficiency \( \eta_2 \) should be close to one if the wavelength of the photons is greater than the absorption limit of the WLS fiber. The trapping efficiency \( \eta_3 \) depends on the numerical aperture of the WLS fiber and is determined by the fiber manufacture. Typically it is between 4\% and 10\% if the wavelength shifted photons are readout from only one end of the fiber without considering the reflection from the other end. The quantum efficiency of the SiPM in ref. [1] made in Russia is about 15\%, similar to the average quantum efficiency of the PMT used in the DESY study. This technology has made great progress since its invention.
just a few years ago and will certain improve further in near future. The quantum efficiency of
the new SiPMs manufactured by Hamamatsu has already approached ~30% as reported in the
2005 ALCPG Snowmass workshop. Fig. 6 shows the photoelectron peaks by using a
Hamamatsu prototype H100 SiPM. It demonstrates the remarkable capability of this new photon
detector technology. With a 100 pixel device, photoelectron peaks up to 60 pe’s are visible.

![MPC-100](image)

Fig. 6. Photoelectron spectrum obtained by a Hamamatsu H100 prototype silicon photomultiplier.

With square or rectangular Cherenkov radiator plate, we expect to lay the fibers on to the top
surface in the direction of Cherenkov light cones to maximize the light collection efficiency.
Depending on the size of the radiator, multiple turns or spiral shaped fiber arrangement can be
considered. Fiber aerial coverage fraction in the range of 10% to 20% should be sufficient since
the multiple light reflection will further improve the light collection. The light collection
technique should be optimized by Monte Carlo simulation and tests.

We expect that the combined conversion efficiency from produced Cherenkov photons to
photoelectrons can reach about 1% when the fiber size, the fiber aerial coverage and SiMP
coupling, etc. are optimized. If we can achieve this level of conversion efficiency, the number of
photoelectrons collected by a photon detector attached to one end of the fiber for a minimum
ionizing particle with $\beta \sim 1$ penetrating a 2.5 cm thick high density lead glass will be between 6
and 9 if we use the radiator materials listed in Table 1. Based on this analysis, we expect that the
number of photoelectrons will not be a limiting factor for achieving a reasonable energy
resolution based on Cherenkov radiation with WLS fiber and SiPM readout.

(2). Directly collect Cherenkov light by SiPM

It is possible to consider mounting a SiPM directly on the top surface of the Cherenkov radiator
without the WLS fiber if the size of the radiator is not too large. The active area of the current
SiPM is only 1 mm$^2$ and the light collection will be quite low by using this method even we
include the enhancement due to photon multiple reflections. However, we do not expect that the
total number of photoelectrons collected in a shower to be the limiting factor determining the
performance of the compensation as discussed above. The situation also will improve when
larger active area SiPMs that are under development by industry become available.
Proposed Plan of Work

- Investigate the response and energy resolution of the scintillator and Cherenkov radiator hadron calorimeter. Optimize the detector design to accomplish the compensation.

- Investigate the performance of Particle Flow Algorithm of the hadron calorimeter using Cherenkov radiator. Optimize the detector granularity to accomplish the separation of showers induced by charged and neutral particles.

- Develop a conceptual design of a hadron calorimeter constructed from lead glass glass crystals and plastic scintillator plates.

- Determine the light yields of lead glass crystals read out with waveshifting fibers and/or with Silicon PM's as a function of crystal material, geometry and surface treatment.

- (If the initial studies demonstrate feasibility) Construct a prototype and demonstrate its performance in a test beam.

Broader Impact

This research direction of proposal, if funded will contribute to the knowledge base in our Physics Department. The beneficiaries of that will be postdocs and graduate students. If the research is successful, results will not only be useful to the future International Linear Collider, but also can be applied to other high energy particle physics experiments.

Results of Prior Research

The University of Washington group has been working on GEM based digital calorimeter in collaboration with the University of Texas at Arlington since 2004. We received funding from DOE through University of Oregon in 2005 to develop a DAQ system that supports the cosmic ray test of GEM chamber stack under construction at UTA. This work is progressing well. In recent years, the UW group has worked on a number of large detector development projects, including the ATLAS muon system design and construction, the D-zero forward muon system construction and the D-zero silicon microstrip detector tracking upgrade project for RunIIb. We have also worked in collaboration with IHEP in Beijing on developing a new type of RPC chambers for the muon detection. All these detector development projects were highly successful and have resulted a number of instrumentation papers in NIM and IEEE Transactions on Nuclear Science that are listed in the Biographical Sketch of the investigator of the University of Washington.

Dr. Adam Para of Fermilab has been doing ILC calorimeter related detector design studies and Monte Carlo simulations, in particular the PFA studies. Dr. Para has extensive experiences in calorimeter and muon detector development for high energy and neutrino physics experiments. He has authored a number of instrumentation papers on the subject of calorimeters based on high pressure gas and scinitllators with WLS fiber readout in recently years.
Facilities, Equipment and Other Resources

The University of Washington Physics Department has a small electronics shop that can design electronics boards, etch and drill printed circuit boards. The Elementary Particle Experiment Group at UW has extensive history in HEP detector development, particularly in gas detector development and construction. Recently we have just completed a large detector construction project that involved building ~32,000 high precision drift tubes and 80 high precision chambers for the ATLAS forward muon system in our laboratory. We have a gas mixing system, some NIM, CAMAC and VME based readout electronics.

Our Physics Department machine shop is one of the largest physics department machine shops in the United States. We have available four CNC mills, two CNC lathes (turning centers), a wire EDN machine, the Dysecker, five conventional lathes and four conventional mills with digital readout. In addition, we have clean-room facilities with temperature control available. The machine shop is staffed with six experienced machinists and tool & dye makers. The joint work with mechanical engineering gives us access to the Department of Mechanical Engineering composite materials laboratory, which has available for our use a hot press and oven. We also have access to a larger oven in the Department of Material Sciences, which we used for fabrication of the D0 silicon vertex detector layer 0 installation tooling. The Physics Department machine shop provides facilities on a cost-sharing basis. The Physics Department contributes two-thirds of the cost on a cost-share basis for certain research projects.

FY2006 Project Activities and Deliverables

- Establish Monte Carlo models so that realizable and realistic results can be obtained.
- Perform initial calorimeter simulation and detector optimizating
- Perform small scale prototype tests and report the results in conferences.
- Investigating the source and quality of high density lead glass.

FY2007 Project Activities and Deliverables

- Perform detailed simulation to compare the performance of various detector configurations for compensation and cluster separation techniques.
- Continue prototype tests
- Submit paper(s) for conferences and instrumentation journals.

Budget justification for University of Washington

We request support for a post-doctoral associate who will perform Monte Carlo simulations to verify the design concept of the dual readout calorimeter described in this proposal and conduct small scale test to provide technical information for the design studies. We also request a small amount of funding for materials and supplies need for these studies and tests. The purpose of these tests will be providing technical information for general design studies.
Two year budget in then year K$ for University of Washington

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Notes
Fringe Benefits calculated at 23.2% for PostDoc (research) staff
Indirect Cost of 55.5% applied to PostDoc salary/fringe benefits and travel

More collaborators

A number of Fermilab physicists have expressed interests in this project and may join in at a later stage. Also, the IHEP (Beijing), China and HEP group from the University of Science and Technology of China have expressed interests in participating.

References: