Proposal to DOE/NSF for ILC Detector R&D

February 22, 2005

Proposal Name

Design and Prototyping of a Scintillator-based Semi-Digital 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 propose to develop, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet energy measurement using particle-flow algorithms (PFAs). Software simulations/algorithm development and hardware prototyping are envisaged as the two main components of our efforts. This proposal addresses the second component while the first is the subject of a separate proposal. The end goal of this research project will be the development of reliable performance and cost estimates for scintillator-based hadron calorimeter options suited for, but not limited to, an e^+e^- linear collider. This will be achieved by the construction and operation of a prototype in a hadron test beam.

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 hadrons 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 very high voltages 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 *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 processing and data acquisition. Reducing the dynamic range of the readout is a potential solution. Monte Carlo studies have shown that this is indeed a promising possibility 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) which 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.

Results of Prior Research

To date we have received two grants for work related to the project described here. The project titled "Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter" was 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

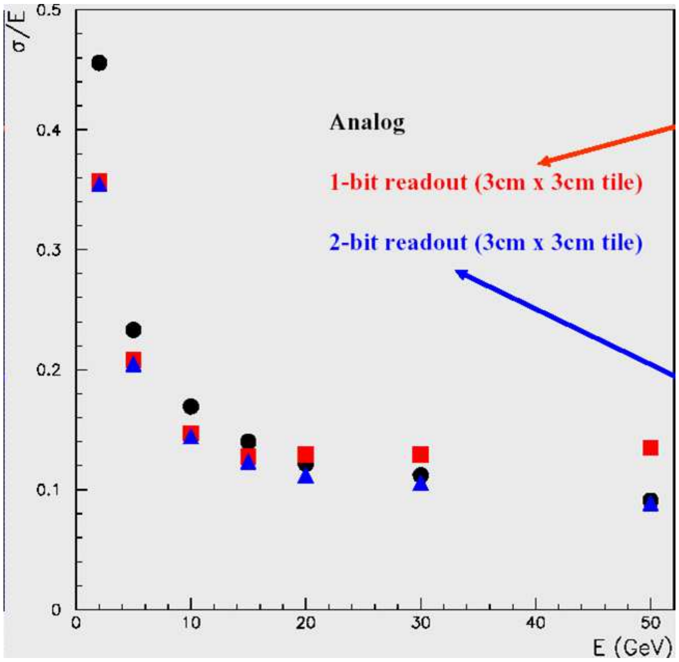

Figure 1: Single hadron energy resolution as a function of the incident energy.

"Planning Grant" while in 2004 we were awarded a one year $50K DOE/NSF grant. 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

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 ($\approx$ 50V) and insensitivity to magnetic fields. On the 1mm^2 sensor surface there are

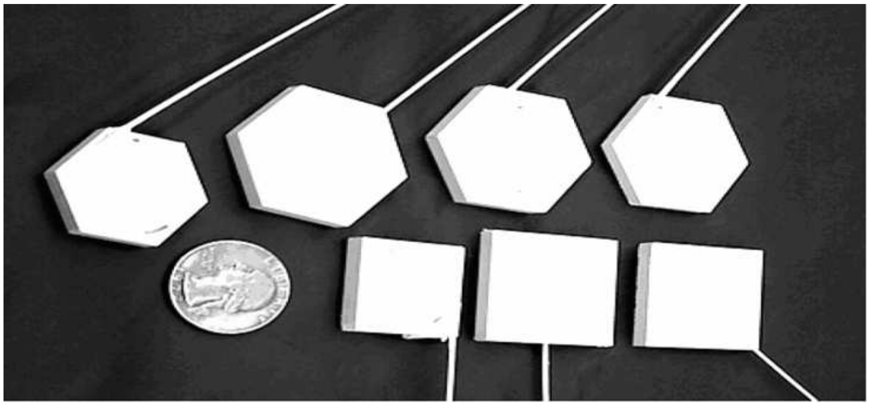

Figure 2: The different species of cells and grooves investigated.

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).

The mounting of the SiPMs on the scintillator tile (see Fig. 4) 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].

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:

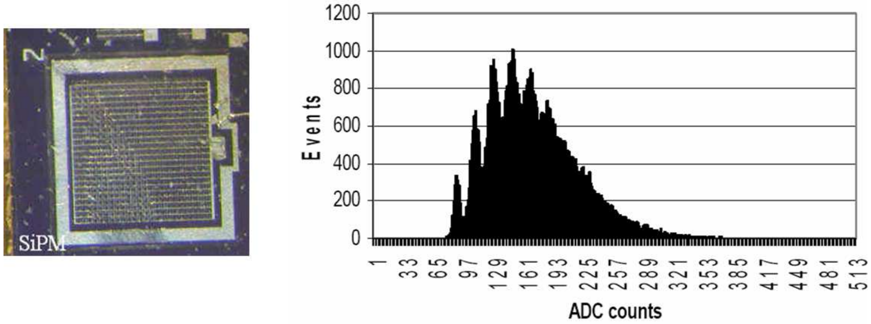

Figure 3: Pixellated surface of the SiPM sensor (left) and single photoelectron separation observed with a SiPM (right).

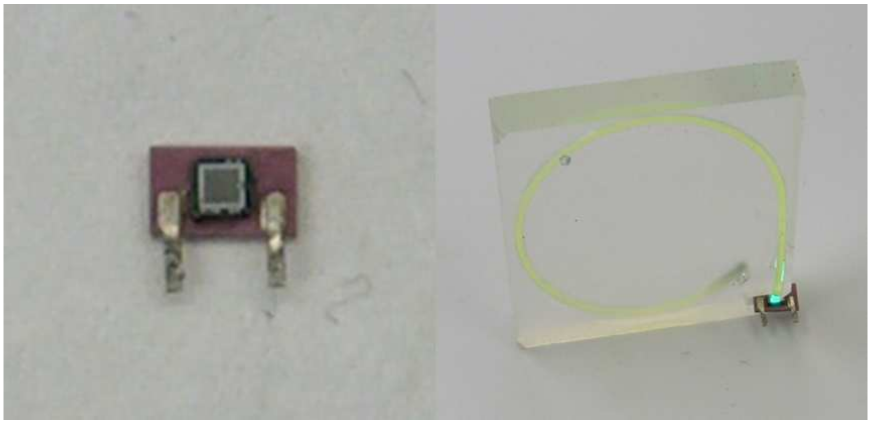

Figure 4: The SiPM sensor mated with a 1mm WLS fiber and embedded in a 3cm x 3cm tile.

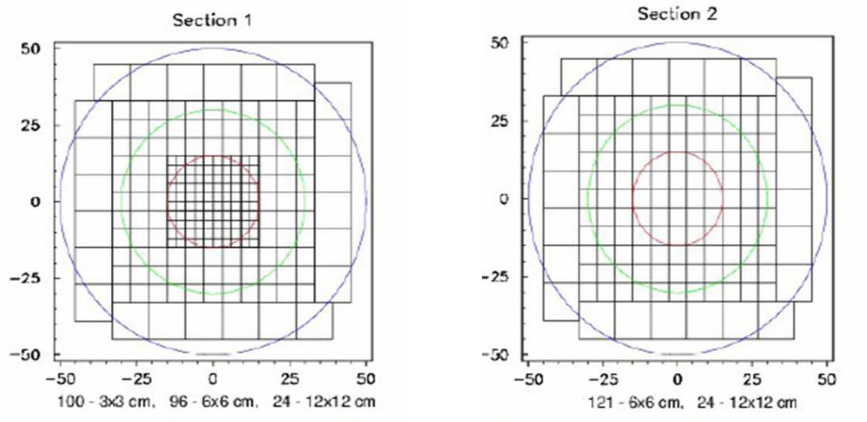

Figure 5: Prototype geometry.

(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 5mm thick scintillator tiles sandwiched between 2cm thick steel absorber plates mounted on a movable table. In reality the absorber is split into three parts: 1.6cm absorber plate and two 0.2cm 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: 3cm x 3cm, 6cm x 6cm and 12cm x 12cm (see Fig. 5). The 3cm x 3cm 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 1mm 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 supported on a G-10 plate which also has the reflective VM2000 glued to its tile-facing side.

Planned R&D

Prototype Operation: The scintillator hcal prototype will be exposed to a hadron test beam at Fermilab during the 2005-2007 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 two 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 SiPMs and carry the necessary electronics and signal/bias traces. The goal is to have robust and cheap electronics with the following functionality:

(a) Preamplification (gain of 10-20) .
(b) Multiple thresholds (cascading discriminators or time over base are possible options).
(c) Good time resolution.
(d) Electronic charge injection.
(e) Temperature monitoring.

For the full detector the most economical solution will be a custom ASIC which encompasses all of the above mentioned functionalities. For our R&D studies however we will be interested in fabricating a prototype system of 500-1000 channels (10% of the channel count for the test beam hadron calorimeter prototype) with discrete elements. This will help us identify and solve electrical and mechanical issues associated with such a design at a fraction of the cost required to develop an ASIC. It will be fairly straightforward to test a prototype of this system with the current hadron calorimeter prototype under construction. This task will be carried out in collaboration with Fermilab electrical engineering department.

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.

FY2005 activities and deliverables

1. Assembly of the Scintillator HCal prototype,
2. Commissioning of the prototype,
3. Design of integrated semi-digital electronics.

The first year deliverable, in collaboration with our European colleagues, is a commissioned scintillator hadron calorimeter prototype.

FY2006 activities and deliverables

1. Operation of the HCal in hadron test beam,
2. Fabrication and testing of the electronics,
3. Installation of the electronics in a few layers,
4. Design of source and LED based calibration system.

The second year deliverable is a prototype accumulating data in a hadron test beam followed by test runs with the new semi-digital electronics.

FY2007 activities and deliverables

1. Fabrication and testing of new calibration system,
2. Installation of new calibration system in a few layers,
3. Continued calibration, monitoring and data analysis.

The third year deliverable will be a Conceptual Design Report on a scintillator hadron calorimeter, for the ILCD, based on our test-beam experience.

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

FY2005: 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 (1.0 FTE). Undergraduate students will participate in the task during the summer months. The equipment and M&S costs relate to photodetectors (SiPMs for two-thirds of the inner core) and integrated semi-digital electronics design and development (layout, test boards, power supplies, test fixtures etc.).

FY2006: Operation of the test beam, calibration and analysis of the data, fabrication, testing and installation of the semi-digital electronics will be done with the additional support of a post-doctoral associate (1.0 FTE). Support for 1.0 FTE graduate students will be maintained. Summer support for undergraduates will be continued. The equipment costs relate primarily to the fabrication of the semi-digital electronics board for installation into the prototype.

FY2007: Fabrication, testing and installation of the new calibration system constitute the equipment and M&S costs. This and the continued analysis of the collected data would require continued support of the post-doctoral associate and graduate student.

The travel funds (2005-2007) 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.

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

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	43.0	44.0	87.0
Graduate Students	21.0	21.5	22.0	64.5
Undergraduate Students	4.0	4.5	5.0	13.5
Total Salaries and Wages	25.0	69.0	71.0	165.0
Fringe Benefits	0.3	23.1	23.7	47.1
Total Salaries, Wages and Fringe Benefits	25.3	92.1	94.7	212.1
Equipment	30.0	25.0	20.0	75.0
Travel	5.0	5.0	5.0	15.0
Materials and Supplies	10.0	7.5	7.5	25.0
Total direct costs	70.3	129.6	127.2	327.1
Indirect costs (45% of non-equipment)	18.1	47.1	48.2	113.4
Total direct and indirect costs	88.4	176.7	175.4	440.5

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

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