PIRE: Calorimetry for the International Linear Collider (preliminary proposal)
NSF Program area: Mathematical and Physical Sciences (MPS)
Specialization: High-Energy Physics

List of participants

Institutions and Personnel requesting funding: (* = undergraduate student; ** = graduate student)

Northern Illinois University: Dhiman Chakraborty (PI), Jerry Blazey, Alexandre Dychkant, Kurt Francis**, Guilherme Lima, Robert McIntosh**, Michael Smith*, Victor Rykalin, Vishnu Zutshi;

University of Oregon: Raymond Frey (Co-PI), Jim Brau, David Strom, Jeff Kolb**, Jinrui Huang**, Elizabeth Ptacek**, Andreas Reinsch**, Mary Robinson**, Jan Strube**, Asher Tubman*

University of California, Davis: Mani Tripathi (Co-PI), Richard Lander, John Stilley**, Cherie Williams*.

University of Texas, Arlington: Jaehoon Yu (Co-PI), Heather Brown*, Carlos Medina**, Jacob Smith**, Andrew White.

US collaborators (Group leaders):

Fermi National Accelerator Laboratory (*Fermilab*): Marcel Demarteau;

Stanford Linear Accelerator Center (*SLAC*): Martin Breidenbach;

Argonne National Laboratory (*ANL*): Stephen Magill.

International collaborators (Group leaders):

Deutches Electronen SYnchrotron (*DESY*), *Hamburg*, *Germany*: Felix Sefkow;

Laboratoire de l Accelerareur Lineaire (*LAL*) *Orsay*, *France*: Jean-Claude Brient;

Laboratoire de Physique Corpusculaire (*LPC*), *Clermont-Ferrand*, *France*: Pascal Gay;

Laboratoire d'Annecy-le-vieux de Physique de Particules, (*LAPP*), *Annecy*, *France*: Yannis Karyotakis;

Cambridge University, *Cambridge*, *UK*: Mark Thomson;

Imperial College, *London*, *UK*: Paul Dauncey;

ITC- Il Centro per Ricerca Scientifica e Tecnologica (*ITC-irst*), *Trento*, *Italy*: Claudio Piemonte;

Shinshu University, *Nagano*, *Japan*: Tohru Takeshita;

Delhi University, *Delhi*, *India*: Brajesh Choudhary,

Changwon National University, Kyongnam, Korea: Changhie Hahn.

The US and international collaborators and their groups will participate in the proposed research activities, but will not request funding under the PIRE program.

PIRE preliminary proposal

Title: **PIRE: Calorimetry for the International Linear Collider**
NSF Program area: Mathematical and Physical Sciences (MPS)
Specialization: High-Energy Physics

Integrated Research and Educational Plan with Innovative Model of International Collaboration

The scientific program at the heart of this proposal is the worldwide effort toward the International Linear Collider (ILC) [1]. We propose to further develop and refine the nascent collaborative efforts toward ILC detector development in preparation for future construction of the accelerator and detector complex. By design, the ILC is a highly internationalized endeavor and continued American participation is essential.

Particle colliders are machines that accelerate electrically charged particles such as protons and electrons (and/or their antiparticles, antiprotons and positrons, respectively) to very high energies before colliding them head-on. Today's colliders can achieve collision energies of several tera-electron-volts (TeV) and luminosities around $10^{34}\text{cm}^{-2}\text{s}^{-1}$. The energy of collision often gives birth to heavier particles, which, after a fleeting existence, decay into long-lived particles – electrons, protons, neutrons, and photons, among others. Studies of such processes, by identification and measurement of the final-state particles using particle detectors, reveal the composition and workings of nature at the most fundamental level. The latter half of the last century witnessed dramatic rise in the capabilities of particle colliders (energy, luminosity) and detectors (speed, resolution). These led to discoveries of new particles and symmetries that govern their interactions.

High energy physics (HEP) has thus provided us with a most compelling picture of the composition of the physical universe and its evolution starting from the big bang, but much more remains to be done. Colliders have become the essential tools of HEP and their continued development has been accepted as the assured path towards uncovering deeper secrets of nature and filling in important gaps that still exist in the standard model (theory) of particle physics and cosmology. From the point of view of applications in our everyday lives, the research and development of particle accelerators, detectors, collection and analysis of huge volumes of complex data – all continuously push the boundaries of contemporary technology. The relentless pursuit of higher capabilities have resulted in a long list of technological innovations that have improved the quality of human life through their applications in such diverse fields as medical diagnostics (imaging) and treatment (radiation therapy), information technology (high-end computing, also the worldwide web was born at CERN, the European laboratory for HEP), security (radiation detection techniques), and financial markets (pattern recognition algorithms).

With each discovery answering some of today's outstanding questions, new questions arise to trigger initiatives for tomorrow. The HEP community reached a consensus in 2001 that the ILC should be the next large particle collider facility after the Large Hadron Collider (LHC) [LHC], which will be commissioned at CERN (Geneva, Switzerland) in 2007. While the LHC will collide protons against protons, the ILC will collide electrons against positrons. The two machines will have complementary strengths, and it would be important to operate them simultaneously as much as possible, so the data from each can be used as input to optimize the running mode and analysis priorities of the other. However, the design and construction of the ILC machine and detectors involve considerable costs and technological breakthroughs, many of which are already well under way. Hundreds of physicists from more than 100 institutions representing some 20 nations from North America, Europe, and Asia have joined hands to meet these challenges as efficiently and expeditiously as possible. The goal is to commission the machine and the detector(s) in 2015, followed by operation over a couple of decades or more. The US is a strong contender to host the facility and Fermilab is the leading choice of site in the US.

The investment required in the design, construction, and operation of the project is so enormous that the interested nations worldwide have agreed unanimously that it must be shared by all and the task must be carried out with extreme care. It was realized early that an innovative model of international collaboration, which integrates all research and development activities around the globe, as well as those of training and education of today's youth so they can carry the project through the next several decades, must be established. As a result of much effort in this direction, a model has started to emerge [3,4].

Under this model, a detailed organizational structure with uniform representation from all participating continents has been formed, charges to the various units have been documented, and leaders appointed at all levels. The units have formulated their plans of action and started executing them. Comprehensive international workshops have been held once every year since 1999, rotating between North America, Europe and Asia [5]. In addition, annual workshops are held in each region, with large participation from others. Topical international summer schools have been started to train students in areas of high specialization. In most of these, financial assistance is offered, so as to enhance the uniformity of global representation. In particular, all expenses are paid for the students selected to attend the summer school (only one held so far [6]).

In most cases, there are strong overlaps of R&D interests between different university and research laboratory groups, regardless of national boundaries [6]. The workshops mentioned above are intended to maximize the yield from their efforts through collaboration. But there is another important component of the activities that is internationalized by necessity: working together at major laboratories across the globe. Each major laboratory has some unique and essential facilities. It is particularly important for young undergraduate and graduate students working on long-term projects to gain first-hand experience at these facilities, not only in the US, but also abroad. Early exposure to collaboration with fellow scientists from other parts of the world has become essential. Because of increasing monetary and other investments, HEP is relying ever more on international cooperation. There have been a few occasions already where students and senior members among those seeking funding in this proposal have visited laboratories in Europe and Asia to use their testing facilities to evaluate prototype detector components designed and built in the US. Similar visits in the opposite direction are planned in the coming years. Over the past several decades, students from other countries have made tremendous contributions in large HEP projects at laboratories in the US and Europe, and enriched the pool of scientists. US funding of the proposed collaborative effort can be expected to help generate funding in other countries where we have collaborators. This will help further the trend toward internationalization. Finally, we hope that the ILC will be built in the US, and scientists and students from all over the world will engage in a unique and fruitful research program spanning over decades.

The physics potential of the ILC will depend crucially on the capabilities of its detectors in general, and the calorimeters in particular. A calorimeter is a part of a detector that measures energies carried by particles emanating from the primary collision point. The better the precision of calorimetric measurements, the faster the ILC will be able to fulfill any given physics charter. Four major detector design concepts are taking shape around the world [7]. Three of them have some variations in other respects, but concur well on calorimetry, where the largest investment will have to be made (upward of 30% of the total detector cost). The institutions requesting funds, and most others listed among collaborators have been engaged in ILC calorimetry R&D since 2001 or earlier. Together, they account for the majority of the worldwide effort on the subject.

The considerations noted above make the proposed activities an ideal fit for the PIRE program description. Based on international collaboration, our comprehensive research plan has the following major components:

- Design, construction, and beam test of a scalable full-depth prototype module including silicon-tungsten (SiW) electromagnetic calorimeter (ECal) and scintillator-steel hadronic calorimeter (HCal) layers,
- Analysis of test beam data leading to verification of simulation models whose accuracy is of crucial importance to establish the validity of algorithms that rely on high-resolution imaging,
- Development of a suite of algorithms to maximize the physics potential of the ILC.

All of these above are interconnected in a feedback loop. For maximum effectiveness, they must be done simultaneously. Beam tests will be done at Fermilab. A breakdown into sub-projects and institutional involvements is summarized below (full forms of the abbreviated institution names can be found in the list of collaborators):

1. Silicon-tungsten (Si-W) ECal

- US: U. Oregon (co-PI), SLAC
- non-US: LAL, LAPP, Imperial College, Delhi

The objective is to develop an ECal for an ILC detector using the technology of ~35 interleaved layers of 2.5 mm thick tungsten radiator and highly segmented (~0.25 cm^2), 0.3 mm thick silicon sensors [8]. The radiator aides well-contained showering of electrons and photons, while the silicon is used to measure the shower. The Oregon group is developing a test module using this technology, which will be exposed to controlled particle beams (a beam test) starting in approximately one year. We plan to carry out the full test at Fermilab, working among and with an international contingent of ILC colleagues. In Europe, a similar but technologically different approach to the ECal is underway [9]. We hope to interact closely with this effort, both in the development of the instrumentation itself, as well as in the data analysis methods for the test data. Refinements, with input from all parties, can then be included for a future round of beam tests. In this way, we should optimize the eventual detector. Our students will benefit from these collaborations involving exchange visits to laboratories and conferences, as will the project itself.

2. Scintillator-Steel HCal

- US: NIU (PI), Fermilab
- non-US: DESY, ITC-irst, Shinshu

The objective is to develop a HCal with ~35 layers of plastic doped with scintillating dye interleaved with 2 cm thick steel absorbers [10]. Each scintillator layer is segmented into “cells” 4-9 cm^2 in area. The roles of the Scintillator and steel are similar to those of the Si and W for ECal, but there are differences in that the HCal is designed to measure heavier particles, that deposit their energies primarily through strong nuclear, rather than elecromagnetic, interactions, and are not contained within the ECal. The HCal is placed downstream of the ECal, and is much thicker. Scintillation light is generated when charged particles - primaries from the central collision, or secondaries arising from the interaction of the primaries in the material medium of the detector - pass through the plastic. The light is collected with a wavelength-shifting fiber embedded in the cell, and guides it to a tiny ($1mm^2$x 0.2 mm) silicon photosensor called “SiPM” mounted on the cell, which converts the optical signal to an electrical pulse.

The NIU group has conducted extensive studies of the scintillator media from different sources and produced using different technologies, with different shapes and surface treatments of the cells, different types of fibers and embedding schemes, and tested SiPM's from different manufacturers [11,12]. They built a 12-layer thick, 7-cell wide (hexagonal cells in a honeycomb arrangement) that was successfully tested with cosmic rays. They are now collaborating, within the “CAlorimetry for the Linear Collider Experiment” (CALICE) collaboration, with a group of several European institutions led by DESY on the scintillator-steel HCal project [13]. The CALICE team has built a full-depth prototype, roughly 1m x 1 m x 2.5 m in dimensions and weighing 15 ton, which is currently being tested with controlled-particle beams at CERN. NIU has built a 16-layer tail-catcher/muon-tracker (TCMT) stack that sits behind the HCal to detect particles that penetrate the HCal. The TCMT is similar to the HCal except that the layers are subdivided into strips instead of cells. It is also a part of the current test-beam set-up, and is operating successfully [14]. We plan to bring the whole CALICE test-beam prototype to Fermilab for further beam tests starting in 2007. This will be an intensely international collaboration and an excellent research opportunity for students. However, the design of the current HCal prototype module is not one that can be scaled up to the full detector. The NIU group plans to play a key role in developing a scalable prototype that can be exposed to test beams in 2-3 years' time. New options, such as fiberless photodetection, will also be investigated.

3. Integrated electronics

- US: UC Davis (Co-PI), Fermilab
- non-US: Imperial, LPC, Delhi

The Davis group is involved in the design of the Application-Specific Integrated Circuit (ASIC) chip to be used for reading out the signal from both the ECal and the HCal. The group has a long history of developing custom electronics for high energy physics and training students in the areas of design, fabrication and testing [15]. A large number of undergraduate students, both within an REU program and outside of it, have been involved in these electronics projects. UCD is responsible for finding solutions for inter-connection issues for the silicon-tungsten calorimeter, using technologies such as indium bump-bonding, hybrid flex cables and solder dot connectors. The bump-bonding process, developed by Prof. Lander at UCD, is a unique facility of its kind in the country. For the hadronic calorimeter, UCD will work on developing custom readout solutions for SiPM devices. The Delhi group, which has experience in designing and building calorimeters using scintillators, as well as assembly and testing of silicon devices, will work closely with UCD on the above projects.

4. Simulation

- US: NIU, UTA (co-PI), SLAC, Fermilab
- non-US: LAL, DESY, Cambridge, Changwon

Accurate simulation of interaction of different types of particles, carrying different amounts of energy, with different material media, plays an essential role in the design optimization of particle detectors in general, and calorimeters in particular. Many models based on large bodies of data are available, but none have been tested at the level of spatial resolution and precision that are pertinent to the ILC. As our current hardware technology and geometry choices as well as algorithm development rely on simulation results based on those models, the data gathered from beam tests of our prototype modules will provide valuable calibration of the models. Thus, such beam tests are important not only to the ILC, but also for calorimetric simulation for other future HEP projects.

The groups listed have considerable experience in simulation, and have applied the same to ILC R&D over the past several years. The NIU group developed an interim program, that served as the standard for simulating detector response for the entire ILC community in the US for two years, before being replaced recently by a more versatile one developed at SLAC. They have also developed a program to parametrically simulate all processes between the deposition of energy in the sensitive volume of the detector to its electronic read-out (e.g. noise, cross-talk, non-linearities, random fluctuations etc.), which has been adopted as a standard in the US and by CALICE [18].

The UTA group has been working on a new idea for HCal using the Gas Electron Multiplier (GEM) technology [19]. The GEM is essentially a thin copper foil with closely spaced and carefully machined holes ~70 micron in diameter, that is maintained at a high electrical potential. High-energy particles charged particles ionize the gaseous medium. The ions trigger an avalanche multiplication at the holes, which is subsequently registered. A GEM-based HCal can be segmented into smaller cells than is possible with scintillators, although the signal from each cell contains less information. The UTA team, which is also a member of the CALICE collaboration, will test through simulation, prototyping and algorithm development, what the trade-off may mean to the overall performance [20].

5. Algorithms

- US: NIU, Fermilab, SLAC, ANL, UTA
- non-US: Cambridge, LPC, Shinshu

The novel technology and design choices for the calorimeters are motivated by the desire to maximize the precision of jet energy measurement. A jet is comprised of a number of collimated high-energy particles, arising from the primary collision. On average, 65% of a jet's energy is carried by electrically charged particles whose momenta (and therefore, energies) can be measured with much higher precision in the magnetized tracking volume even before they strike the calorimeter. Thus, the overall jet energy resolution could be improved dramatically if the energies deposited in the calorimeter by the charged particles could be separated from those by the neutrals, and the calorimetric measurement is used only for the latter. This is what a new class of algorithms, known as “Particle-Flow Algorithms” (PFA) aim to do. However, separation of energy deposits (“showers”) by individual particles require fine three-dimensional segmentation of the calorimeter, as described above. Many of the participants and collaborators - NIU, SLAC, ANL, Cambridge, LAL, LPC - have performed extensive development and studies of PFA's [21, 22]. Based on simulation of ILC detector models, some implementations have achieved performance close to the target at a benchmark point, but much further work is needed to optimize and establish the viability of PFAs for general application. Should PFAs prove inadequate, we'll explore alternative designs and algorithms.

Fermilab, SLAC, DESY, and LAL are, and will continue to be, key providers of support for electronics, engineering, and software for all of the above efforts.

A few notable points:

- The plan makes excellent use of, and will further strengthen, the existing facilities, organizational infrastructure, knowledge base, and collaborative relations in a truly international network.
- Our investigation will help invigorate R&D of a newly emerging class of photon detectors commonly known as silicon photo-multipliers (SiPM). These ultra-compact compact, rugged, radiation-hard, and amazingly economical devices can operate at room temperature, inside strong magnetic fields, and under a nominal electric potential. Consequently, they can be expected to replace conventional vacuum tube devices, which share none of above strengths and cost tens of times more, in many applications. SiPM's are also opening up new applications. They are poised to make revolutionary impact on many fields including medical diagnostics, security, and basic research [23]. Over the

past three years, NIU and DESY have acquired extensive experience in detailed evaluation of SiPM's. ITC-irst is a new manufacturer of SiPM's that we propose to work with. We will study SiPM's from other sources as well. Fermilab will also study SiPM's and provide packaging suitable for their application to ILC calorimetry.

- More than a dozen graduate and undergraduate students at the participating institutions are already involved in ILC calorimetry R&D. The nature of the program will help us enhance their first-hand experience of international scientific endeavor by working at laboratories abroad and attending international workshops and conferences. Non-US collaborators will reciprocate by sending their people to participate in beam tests at Fermilab and to conferences in the US.
- We have set a precedence among US universities by making a whole-hearted commitment to the ILC early. Similar commitments from more institutions are needed if the US is to play a central role in this major international undertaking. Recognition of our initiative will send a strong signal of encouragement.
- The participants have strong record of achievements from prior support. They have received funding for ILC work from the NSF, and the US Departments Of Energy and Education.

Although there is strong interest and commitment among the participants, and they have produced a good deal of progress over the years, they have so far received funding that is small in comparison to their counterparts in Europe and, in some cases Asia, and only on a year-to-year basis. This has put not only calorimetry, but all ILC detector development efforts in the US, at a disadvantage by limiting the planning options. It is also very difficult to attract students and post-doctoral researchers to projects whose continuation must be decided yearly based on the availability of funds. The requested funds, if granted, will go a long way to alleviate these impediments by ensuring viability over a longer period, which is necessary for most pieces of our planned activities. It will help us strengthen the partnership between the participating US institutions and their overseas counterparts by promoting bilateral exchange of ideas and information through personal contact and access to instrumental facilities.

We propose to use most of the funds to pay for salaries and international travel of students and post-doctoral researchers, with the rest going to senior personnel travel. Although substantial costs are involved in procurement of materials and supplies, the current short-term funding from other sources can be used for that purpose. In conclusion, we wish to emphasize that the proposed program of activities is driven by the need to establish and maintain a multilateral collaboration as an example of internationalized science and in preparation for the already scientifically compelling international collaboration. Both science and this specific project must have well-funded and developed global collaborations to succeed in the future.