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

1 Introduction

The University Consortium for Linear Collider R&D (UCLC) [1] incorporates work at 20 US universities on 27 different R&D projects related to the Linear Collider. Of these projects, 15 cover the previously identified detector R&D needs of the Linear Collider [2]. This document summarizes these. A separate document from the UCLC consortium focuses on accelerator R&D. The large participation in these proposals expresses the high level of interest in university groups in the Linear Collider, their excitement about the physics to be done with the instrument, and their conviction that the Linear Collider represents the future of the field.

1.1 Preamble

There is a now a worldwide consensus that the next large facility in particle physics should be an international high energy electron-positron collider. This consensus recognizes the central importance of the physics to be studied, as well as the maturity of accelerator designs being simultaneously advanced (and proposed) at laboratories in the United States, Germany, and Japan. In January, 2002 the US High Energy Physics Advisory Panel (HEPAP) called[3] for vigorous US participation in a Linear Collider effort:

> We recommend that the highest priority of the US program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world. This facility is the next major step in the field and should be designed, built and operated as a fully international effort.
>
> We also recommend that the United States take a leadership position in forming the international collaboration needed to develop a final design, build and operate this machine. The US participation should be undertaken as a partnership between DOE and NSF, with the full involvement of the entire particle physics community.

Response to this consensus has been swift. In early 2002, physicists from US universities and laboratories organized a series of workshops at the University of Chicago, Fermilab, Cornell University, SLAC, and UC Santa Cruz aimed at understanding fruitful directions for research and collaboration towards the Linear Collider. The hundreds of technical issues involved in the design and construction of the accelerator and detector emerged as an organizing theme. UCLC organized itself to consider these issues in the context of NSF support, and the Linear Collider Research and Development Working Group (LCRD)[4] did likewise in the context of DOE support. The two groups are naturally intermingled with each other. All concerned are working together within the American Linear Collider Physics Group (ALCPG)[5] to coordinate their activities to the single task of building the linear collider.

Taken together, the LCRD and UCLC proposals mark a fundamental change in the level of engagement of US universities in the Linear Collider. In the year 2001, Linear Collider work was supported at fifteen US universities, and the work was largely confined to physics and detector simulation studies. This proposal, together with the UCLC accelerator R&D and LCRD proposals, nearly quadruples the number of institutions, with most participants having had no prior affiliation with the Linear Collider effort. The detector projects request support to move beyond simulation, into prototyping of real devices. The increase in numbers follows on the Snowmass consensus, and the excitement and commitment of the US university physics community toward making the Linear Collider a reality.

1.2 Physics Goals of the Linear Collider

The physics goals of the Linear Collider are ambitious and compelling. The Linear Collider is needed to address a central issue in particle physics today, the origin of mass and electroweak symmetry breaking. Over the past decade, a wide variety of experiments has shown that elementary particle interactions at the TeV scale are dictated by an $SU(3) \times SU(2) \times U(1)$ gauge symmetry. The non-zero masses of the W and Z particles imply, however, that the electroweak $SU(2) \times U(1)$ symmetry is broken spontaneously. We do not know how the symmetry is broken, and we will not know until the agents of electroweak symmetry are produced directly in the laboratory and, also, are studied in precise detail. But we have every reason to believe that whatever is responsible for electroweak symmetry breaking will be accessible at the Linear Collider.

In the so-called Standard Model, one doublet of scalar fields breaks the symmetry. This model has one physical Higgs particle, which is the window to electroweak symmetry breaking. The global consistency of precision electroweak measurements gives this model credence, and suggests that the Higgs boson is relatively light, $m_H \leq$ 200 GeV. However, this model works poorly beyond TeV energies. A theoretically preferable scenario is based on supersymmetry (SUSY) at the expense of a whole new spectrum of fundamental particles and at least five Higgs states. The lightest of these states looks much like the Standard Model Higgs, with nearly standard model couplings and a mass less than 200 GeV or so. Nature may break electroweak symmetry through some other mechanism, but most realistic mechanisms we have imagined result in a Higgs boson or some related phenomena accessible to the Linear Collider.

The ongoing Run II at Fermilab's Tevatron has a chance of getting the first glimpses of the agents of electroweak symmetry breaking. Starting later in the decade, CERN's LHC, with seven times the energy, will almost certainly observe the Higgs boson, and has a very good chance of discovering something else. Most high-energy physicists believe, however, that the LHC will not unravel the mysteries of symmetry breaking on its own. Experimentation at a linear e^+e^- collider provides information that cannot be obtained by other means. Let us just cite two examples. First, a series of cross section and branching ratio measurements will trace out a detailed profile of the Higgs boson, in a model-independent way, and incisively test whether its couplings are proportional to mass. Second, if SUSY is at play, the Linear Collider can determine the lightest superpartners' masses with exquisite precision. Since the LHC measures mass differences more precisely than the masses themselves, a single Linear Collider measurement will significantly advance the program of SUSY measurements at the LHC. In both these cases, the Linear Collider adds critical information to what will be learned at LHC.

The full scientific case for the Linear Collider can be found in the Resource Book [55] prepared for Snowmass 2001 or the physics chapter of the TESLA Technical Design Report [56]. The physics case is persuasive, and we are responding by banding together to meet the technical challenges that remain, so that the instrument can be built in a timely and cost-effective fashion.

1.3 The Need for Detector R&D for the Linear Collider

The physics case for the Linear Collider (LC) requires a starting center-of-mass energy of 500 GeV, upgradeable to the vicinity of 1 TeV, and a luminosity of a few $\times 10^{34}$ cm^{-2} s^{-1}, a sobering 10,000 times that achieved at the SLC. This level of performance is sufficient for the wide range of precision measurements needed to understand the Higgs mechanism and its role in electroweak symmetry breaking.

To exploit the full physics potential of a 500 GeV LC, the detector must move well beyond the designs of the LEP/SLC era, and beyond the current state of the art. The detector development for the LHC experiments has advanced the art, particularly extreme rate capability and radiation hardness. The LC has somewhat different requirements: hermeticity, track momentum resolution, jet energy resolution and the identification of b and c flavored jets. Specifically, relative to the LHC, the LC requires [2]

- 3-6 times closer inner vertex layer to the interaction point (higher vertexing precision)
- 30 times smaller vertex detector pixel sizes (improved position resolution and two-track separation)
- 30 times thinner vertex detector layers (reduced multiple scattering and photon conversions)
- 6 times less material in the tracker (better momentum resolution and reduced photon conversions),
- 10 times better track momentum resolution (better event selection purity) and
- 200 times higher granularity of the electromagnetic calorimeter (better jet energy resolution).

One can hope to reach these goals because the demands on readout speed and radiation hardness are mild compared with the LHC.

The detector that meets these goals will enable tagging of a Higgs that is recoiling against a Z that is precisely reconstructed in a dilepton decay; precision measurement of the masses of SUSY particles by pinpointing the endpoints of the box spectra of their decay products; discrimination of W and Z bosons for studies of Higgs couplings and strong WW and ZZ scattering; precision measurements of the couplings of the Higgs to the b and c quarks. The specific demands on each detector element will be discussed in later sections.

1.4 Broader Impact of the Work described in this Proposal

The design, construction, and utilization of the Linear Collider (LC) offers profound opportunity for the engagement of university-based physics and engineering groups, and will pay back large dividends of intellectual stimulation and scientific discovery.

The detector development work proposed here has benefits beyond the LC. Although the work is aimed at specific issues relevant to the LC, much of it is applicable to other areas of high energy physics, whenever high accuracy is required in a relatively low rate environment. Devices and techniques targeted at the high precision, low duty cycle, low rate, and relatively low radiation environment of the LC complement well the detector development driven by the LHC environment, which is characterized by high rates and substantial radiation.

In the past, developments in high energy physics instrumentation have found widespread application in other fields, such as medical imaging. It is to be expected that detector development for the LC will likewise have significant spinoffs in other fields of science.

An important part of this program is education and public outreach. We will create UCLC Fellowships and Scholarships to enable High School teachers (UCLC Fellows) and High School students (UCLC Scholars) to participate in the research outlined in this proposal, working side-by-side with university physicists. These students and teachers will carry forth the excitement and stimulation of science and technology into the larger community, and some of the students will go on to become the next generation of scientists and engineers.

UCLC groups will also continue ongoing education and outreach efforts, incorporating the excitement of physics at the energy frontier whenever possible, and they will engage both undergraduates and graduate students in the proposed research.

1.5 Structure of this Overview

The detector projects can be broadly categorized into five general areas of study. In the sections below, we outline the critical R&D issues associated with each, and explain how the proposal addresses these issues. More detailed descriptions of proposed individual UCLC projects, including budgets, statements of work, and deliverables may be found in the Appendix and at `http://www.lns.cornell.edu/public/LC/UCLC/projects.html`.

Section 7 presents the UCLC education and outreach program and Section 8 outlines the plan by which the projects will be managed.

2 Machine Detector Interface

Many precision measurements at a future LC will depend on precision determination of the initial state of the colliding beams: their energies, luminosities, and polarizations. The diagnostic instruments required for these measurements lie beyond the scope of "necessary" accelerator instrumentation, since they are not required in order to deliver high-luminosity beams. They are provided by experimentalists working closely with the accelerator physicists on the design, construction, and commissioning of the equipment so as to insure their physical and operational integration into the accelerator infrastructure. Past successes of these projects at CESR, SLC, and LEP and their influence on the physics of the experiments bear out the importance of these collaborations.

In order to achieve the necessary precision, new techniques for measuring beam parameters must be developed and proven. A determination of the top quark[8] or Higgs boson mass[9], for example, would require a beam energy measurement with a relative error of $1-2\times10^{-4}$. A measurement of the W boson mass with a threshold scan[10] could achieve a relative error of of 7×10^{-5}, which would place even more stringent requirements on the energy measurement. To date however, no beam energy measurement technique has been shown to work with this precision at beam energies greater than 100 GeV. The detailed understanding of the luminosity spectrum, dL/dE, which is required for particle mass measurements[11], as well as luminosity optimization, is significantly enhanced if the beam parameters and emittances can be determined precisely at the interaction point.

In collaboration with LBL and SLAC, the Notre Dame group **[Project Leader: M. Hildreth; Budget: $357K over 3 years]** plans to demonstrate the mechanical and electrical stability required for a beam energy measurement with a LEP-style[12] magnetic spectrometer using high-precision Beam Position Monitors (BPMs). The BPMs are under development at LBL and SLAC[13]; the group is also in close contact with DESY-Zeuthen who are pursuing a different BPM design for a similar system, and is exploring collaboration on hardware fabrication and beam tests with the UK Linear Collider Acclerator R&D proposal which has recently been submitted to PPARC. Optical techniques for monitoring stability and alignment are being developed in collaboration with Oxford University and the University of British Columbia[14]. The end goal is to produce a prototype BPM station whose beam-test stability will be adequate to achieve the required beam energy measurement accuracy. This project, that at DESY-Zeuthen, and the development of a different beam-energy measurement technique at Oregon/SLAC represent the only international research and development work on energy measurement at a LC.

The Wayne State group **[Project Leader: G. Bonvicini; Other Senior Personnel: D. Cinabro, I. Avrutsky; Budget: $143K over 3 years]** will also work on a system to measure the relative size, position and transverse orientation of the two beams using large angle[15] and coherent[16] beamstrahlung. The devices measure six of the seven transverse degrees of freedom in the beam-beam collision, effectively photographing the collision itself. A prototype has been installed in CESR and significant data taking is imminent. With the experience gained at CESR, plus testing at SLAC and simulation work, sub-nanometer resolution may be possible. Related but complementary work based on the detection of the e^+e^- pairs produced in the beamstrahlung reaction is underway at KEK. Each of these projects is unique in the world LC research and development effort.

Major Machine- Detector Interface Milestones and Deliverables

In FY04, we will assess the performance of a linear and transverse optical reference system based on interferometry. An optics deck for the spectrometer installation in the NLC or TESLA designs will also be produced. The beamstrahlung detector will continue its experiments at CESR, and a preliminary design for a LC beamstrahlung monitor will be produced.

In FY05, we will bring the first mechanical prototypes for supporting the spectrometer BPMs and measurements their stability. The beamstrahlung detector will acquire fast electronics for bunch-to-bunch studies.

In FY06, the spectrometer will see the assembly of the full prototype BPM stand complete with nanomover and a beam test to demonstrate mechanical and electrical stability. The LC beamstrahlung detector design will be completed and the fast electronics commissioned so that bunch-to-bunch studies can be done.

3 Vertex Detectors

The precision determination of Higgs couplings, efficient flavor tagging in multi-jet events, and determination of heavy quark charge all benefit by pushing vertex detector performance to new levels. The World Wide Study of Physics and Detectors [2] concluded that the 3-dimensional impact parameter resolution should be better than $5\mu\mathrm{m} \oplus \frac{10\mu\mathrm{m} GeV/c}{p sin^{3/2}\theta}$. Achieving this goal demands a vertex detector that is thin ($< 0.1\% X_0$/ladder), has a small inner radius (< 1.5 cm), is highly segmented, and has high precision compared with those at the LHC. In order to achieve these goals, it is possible to relax requirements on readout speed and radiation hardness compared with the LHC detectors.

One potential solution is to use CCD's, which have performed well in low rate environments. Resolutions better than 5μm have been demonstrated and, since the active volumes are of order $(20\mu\mathrm{m})^3$, there is the possibility of fabricating detectors that are very thin if a method can be found for supporting them. Compared with the SLD vertex detector, a CCD device for the LC would have to tolerate higher radiation levels from low energy e^+e^- pairs. Furthermore, limiting occupancy due to these pairs demands a readout that is 10 to 100 times faster.

Groups at Oregon/Yale, Niigata, REPIC and KEK and the British Linear Collider Flavor Identification (LCFI) are working on designs for fast CCD's [17]. The Oklahoma & Boston group **[Project Leader: P. Skubic (Oklahoma); Other Senior Personnel: U. Heintz (Boston); Budget: $245K over 3 years]** plans a complementary effort to develop an integrated CCD readout system. The long-term goal is a compact system for managing data acquisition and providing timing and control functions that could be mounted directly on the barrel, close to the front-end hybrids. The group's initial objectives are to develop the specifications for this system, including modularity and the number of gates required, and to identify appropriate design methods and development tools. It will study the use of ASIC's and FPGA's to optimize the design for the LC, and will construct a simple data acquisition stand suitable for testing candidate vertex detectors and readout systems. The Oklahoma/Boston group will leverage the considerable cost involved in CCD development by using the LCFI CCD's in tests of their readout chips.

In view of the timing challenges, particularly in the TESLA machine design, and significant uncertainties in the estimated backgrounds, especially for neutrons, it is important to explore alternatives to CCD's. The Purdue group **[Project Leader: D. Bortoletto; Other Senior Personnel: I. Shipsey; Budget: $197K over 3 years]** will explore methods to produce and mechanically support thin silicon sensors.

Hybrid pixel systems will be used at the LHC since they are radiation hard and can be read out rapidly. For the LC, material must be reduced compared with the LHC detectors in order to achieve excellent impact parameter resolution and to precisely measure low momentum tracks. The Purdue group will produce thin pixel detectors and develop the bump bonding of thin sensors to back-thinned read-out chip wafers.

The Purdue group will also carry out simulations of an LC detector based on hybrid pixel technology in order to quantify its potential performance. The use of thin hybrid pixel detectors in the forward tracking region will also be explored. The addition of disks of thin silicon hybrids perpendicular to the beam line would increase the solid angle coverage of the detector and hence the efficiency. It would also reduce material traversed by forward tracks relative to the LHC style pixel detector proposed for the forward region in the TESLA detector design, thereby improving impact parameter and vertex resolution.

In parallel, the Purdue group will characterize interleaved pixels developed at Fermilab for BTeV to determine if they meet the LC performance goals. This work builds on the achievements of Battaglia *et al.*, who have shown improved resolution using this approach [18]. Together, these studies will contribute to a realistic assessment of the viability of hybrid pixel technology for the LC.

Purdue will also build on their experience with CLEO-III and CMS to fabricate low mass support frames and measure the deflection and stability of thin devices supported by them. This work will be done in close collaboration with a Fermilab group who will be responsible for finite element analysis of the mechanical stability of thin silicon. The Purdue group will remain in close contact with the two other groups studying thin silicon: an Oregon/Yale group investigating ”stretched” CCD's in place of a mechanical support and the LCFI group developing precision supports.

Major Vertexing Milestones and Deliverables

In FY04, we will complete a systematic study of mechanical stability issues for thin silicon and evaluate the performance of interleaved hybrid technology developed at Fermilab. We will specify the parameters of a CCD readout and control system.

In FY05, we will evaluate the impact parameter resolution achievable with thin, interleaved hybrid pixel detectors and will develop and test prototype CCD readout chips.

In FY06, we will optimize the design for a hybrid pixel detector for the LC and will develop the design of the CCD readout chip.

4 Tracking

4.1 Overview of Tracking Requirements

Experimental physics goals for a future LC create challenges for charged particle tracking in regard to momentum resolution, multi-track separation and reconstruction in the forward angle. The momentum resolution goal is driven in part by the need to measure high-energy isolated charged particles [2], expected to be prevalent in new physical processes (supersymmetry, heavy leptons, leptoquarks, *etc.*) as well as Standard Model processes containing high-energy leptons ($t\bar{t}$, W^+W^-, ZZ, $\ell^+\ell^-$, *etc.*). Measurement of the di-lepton recoil mass spectrum in $e^+e^- \to HZ$ with $Z \to \mu^+\mu^-$ is also dependent on momentum resolution. Ensuring that the mass measurement is limited less by the momentum measurement than by the intrinsic beam energy spread demands $\sigma(1/p_t) \sim 2 \times 10^{-5}$ GeV^{-1}[19]. Full exploitation of the physics potential of a LC will place unprecedented demands on the momentum resolution of a collider tracking detector, requiring an order of magnitude more precision than existing or previous collider detectors.

Reconstruction of hadron jets will also be important both in searching for new physical processes and in understanding Standard Model channels[2]. Particle flow algorithms, discussed in the section on calorimetry, demand that all tracks be accounted for and properly associated with calorimeter energy depositions. Meeting these demands requires excellent charged track pattern recognition, two-track separation, as well as definition of particle trajectories at the exit of the tracking detector.

Forward-angle tracking will be important because flagship supersymmetry processes (selectron and chargino production) should have strongly forward-peaked cross sections, as will some important Standard Model processes, such as WW production and, at higher c.m. energies, WW scattering. Adequate monitoring of beamsstrahlung requires precise differential luminosity measurement; the kink angle in outgoing Bhabha electrons must be measured to better than $\approx$0.01 mrad.

4.2 Tracking Technologies and Research Plan

Tracking technologies under consideration world-wide fall into two broad categories. In one, a central chamber, typically a Time Projection Chamber (TPC) or drift chamber, provides a high density of measurements of moderate spatial resolution. In this configuration, the decreased effectiveness of the tracking chamber at small polar angle is compensated with forward tracking devices. In a second option, a silicon tracker, providing a few precise measurement points, occupies the measurement volume. This detector is smaller, which allows for both the integration of additional silicon detectors for small polar angle measurements and the construction of a more compact and cost efficient calorimeter surrounding the central tracker.

An international collaboration of groups centered in Europe and Canada has been formed to study the axial, electron-drift TPC technology [21]. Studies address mechanical design (including electromagnetic field shaping and cooling systems), electronics integration, and calibration. Most critical, however, is research on electron amplification and readout schemes. This, rather than the intrinsic drift mechanism, is the limit of spatial resolution and multi-track separation. The Cornell / Purdue group **[Project Leader: Dan Peterson (Cornell), Other Senior Personnel: Richard Galik, Ian Shipsey (Purdue); Budget: $366K over 3 years]** has initiated a comprehensive, US based, program to address optimization of TPC readout. A TPC readout based on a gas amplification micro-structure such as a GEM or MicroMegas offers improvements in both segmentation and resolution over conventional wire-planes with pads. The Cornell and Purdue groups propose a program of TPC development using various readout systems, to study issues of resolution, segmentation, channel count, signal complication, noise, cross-talk, and ion feedback. The TPC's, a 4T superconducting magnet, and the drift chambers used for track definition will be built by the Cornell group who have extensive experience designing, building and operating drift chambers for the CLEO experiment [22]-[24]. The Cornell accelerator group will provide the superconducting magnet. GEM and MicroMegas readout modules will be built by the Purdue group who have many years experience developing micro-pattern gas detectors [25]-[40]. These studies will be closely coordinated with and complement the European and Canadian work.

An alternative and novel approach in TPC design is to drift heavy ions rather than electrons [41]. The Wayne State / Temple group **[Project Leader: Giovanni Bonvicini (Wayne State); Other Senior Personnel: C.J. Martoff (Temple); Budget: $280K over 3 years]** proposes to investigate the use of a Negative Ion TPC (NITPC) as an LC central tracker. The technology, proven by multiyear stable running of a 1m^3 directional dark matter device, DRIFT [42], has found other practical applications, most notably as a directional neutron detector for national security purposes. By making use of the long drift time, thermal diffusion, and extremely fine longitudinal sampling, the device promises excellent resolution, low material and low cost, and the possibility to operate a gas detector in the Small Detector design [43]. Proposed studies in the first year include 1) TPC drift configurations (axial, azimuthal, or radial) and working point; 2) gain and readout structures (wire, GEM or Micromegas); and 3) novel, low-mass detector planes that take advantage of the very small FADC occupancies.

In a LC detector based on a TPC, the precision is degraded for small polar angle charged particles because of the reduction in the number of measurement points. The importance of forward physics at LC energies and the need for precise differential beam luminosity measurement argue for adding one or more layers of tracking just behind the TPC endplate. One possibility is multiple layers of straw tubes, as incorporated into the TESLA detector baseline design. The Hampton group **[Project Leader: Keith Baker; Other Senior Personnel: Ken MacFarlane; Budget: $200K over 2 years]** proposes to research and develop a straw-tube based wire chamber for forward charged particle tracking. The Forward Chamber (FCH) would cover the TPC endcap. The group will analyze the requirements for the FCH, including detailed detector simulations. The Hampton group has a long experience in building gas chambers and is part of the US group constructing the barrel Transition Radiation Tracker for the ATLAS Inner Detector.

Several silicon technologies, used in compact vertex detectors for more than a decade, have steadily decreased in cost (per cm^2) to the point where they can be considered for use in much larger central and forward trackers. R&D devoted to developing large-area, low-material silicon tracking layers for a LC detector is coordinated by a collaboration of US and European groups [44].

An alternative to silicon microstrips and a very promising technology is Silicon Drift Detectors (SDD) [45]. Pioneered for the STAR Experiment's vertex detector at RHIC, SDD's provide 3-dimensional space points analogous to those of a TPC, but with pixel precision of O(10 μm), giving an advantage in multi-track separation and pattern recognition. The Wayne State / Brookhaven group **[Project Leader: Rene Bellwied, (Wayne State); Other Senior Personnel: David Cinabro (WSU), David Lissauer (Brookhaven); Budget: $462K over 3 years]** proposes to develop a new SDD layout optimized for an LC central tracker but based on the successful STAR design. Specific improvements include the use of larger area, very thin detectors, higher applied drift voltage, lightweight support structures and optimized readout systems. BNL will design and prototype the detectors, support structure, and the electronics and Wayne State will test the prototypes. In addition the group will continue ongoing comparative studies between this future SDD main tracker and competing technologies in terms of pattern recognition, two-track and momentum resolution and track matching to the vertex detector and calorimeter. These studies will be coordinated with the US / European silicon collaboration.

Whether an LC silicon tracker is based on microstrip or drift technology, there will be a premium on minimizing material in the tracking fiducial volume in order to suppress multiple scattering. Ultra-light devices will be less rigid than current devices, and so will be feasible only if methods are available for tracking rapid alignment changes. The Michigan group **[Project Leader: Keith Riles; Budget: $307K over 3 years]** proposes to continue a program of detector R&D and simulations to develop a precise, low-mass, real-time alignment system. The proposed technology is based on an ATLAS-designed frequency scanned interferometer [46] in which hundreds of absolute distances are measured to a precision of O(1 μm) to define an overconstrained geodetic grid for inferring distortions. A demonstration system is being commissioned in a Michigan lab [47] as part of a multi-year program leading to a prototype system. The group has also carried out a series of studies [19],[48]-[50] of the Higgsstrahlung process that have established the momentum resolution needed in order for the beam energy spread (at JLC/NLC) to dominate the Higgs mass smearing. The group is now addressing both the high-energy *and the low-energy* endpoints of the lepton spectra from slepton decay [51].

Major Tracking Milestones and Deliverables

In FY04, we will demonstrate operation of a small electron-drift TPC, design a testbeam negative-ion-drift TPC complete the design and prototype of an LC specific silicon drift detector wafer, complete a demonstration-level frequency scanned interferometer on an optical bench for alignment studies, and construct a small straw-tube wire chamber for irradiation tests.

In FY05, we will systematically study track separation and position resolution with various readout planes in a larger TPC, start construction of a testbeam NITPC, carry out a second iteration of silicon drift detector wafer design and prototyping, carry out detailed measurements of attainable alignment precision with frequency scanned interferometry, and complete irradiation tests of a prototype straw-tube chamber.

In FY06, we will extend the systematic study of track separation and position resolution in the FY05 TPC to include a magnetic field. We will complete and begin operating a test beam NITPC, complete a final prototype of a silicon drift detector ladder, build a partial prototype of a full silicon tracker alignment system, and carry out detailed design and simulations for a straw-tube forward chamber.

5 Calorimeter design, simulations, and algorithm development

5.1 Overview of Calorimetry Requirements

Electrons, photons, jets, and missing energy figure in virtually every important process to be studied at the LC. The physics reach of the LC will thus largely be decided by the measurement precision for the 4-momenta of these objects [2]. For example, it will be important to be able to distinguish a Z or a W boson by its hadronic decay into 2 jets. This means that the dijet mass must be measured to a precision of $\sim$ 3 GeV, or, in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ (E in GeV) [52].

The most promising means of achieving these unprecedented resolutions is through particle flow algorithms (PFA, also known as Energy Flow Algorithms, or, EFA) [53]. PFAs seek to identify and subtract from a jet those clusters of energy produced by charged particles. These particles, which typically carry $\sim$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 PFAs [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 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.

5.2 Calorimetry Technologies and Research Plan

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 medium for the HCal. Hybrids employing multiple technologies are also possible for both the ECal and the HCal. This proposal aims to study some of these options while the rest are pursued by institutions funded by DoE, with all groups working in close collaboration.

The hardware development must proceed in an intimate feedback loop with simulation studies. On one hand, the design optimization must begin with simulation, while on the other, data from test-beam studies of the prototypes 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].

On the hardware front, the NIU & UIC group **[Project Leader: V. Zutshi (NIU); Other Senior Person-**

nel: G. Blazey, D. Chakraborty, M. Martin (NIU); M. Adams, C. Gerber, N. Varelas (UIC); Budget: $533K over 3 years] will investigate the scintillator option for the HCal. Its proposed research is synergistic with that of 3 other groups within UCLC and one in LCRD. This group has made considerable progress in investigating design options and, after careful characterization of the most promising ones, has fabricated a 12-layer stack for cosmic-ray tests. Each layer has 7 hexagonal cells in a honeycomb arrangement. The requisite electronics and data acquisition and analysis systems are in place. They are now collaborating with the Europeans, particularly the TileCal group at DESY, on the design of a test-beam prototype module that may combine the European and American variants of the scintillator-based designs. They are jointly investigating various transducer and readout options. The University of Chicago group **[Project Leader: M. Oreglia; Other Senior Personnel: E. Blucher; Budget: $318K over 3 years]** has begun studying the glass RPC option for the HCal in close collaboration with, and to complement research by, a group from the Argonne National Laboratory. They propose to design some of the readout electronics for the RPC prototypes under study. The group from the University of Kansas **[Project Leader: G. Wilson; Other Senior Personnel: A. Bean, P. Baringer, D. Besson; Budget: $364K over 3 years]** proposes to investigate a hybrid ECal design where thin layers of scintillators augment a reduced number of silicon layers as active media (with W or Pb for the absorber). The idea is to improve the stochastic resolution by increasing the total number of sampling layers without seriously compromising the excellent position-resolution of Si. The excellent timing resolution of the scintillator can also help in bunch identification in a very high frequency machine. This group is collaborating with colleagues in Japan and Italy. The Notre Dame group **[Project Leader: M. Hildreth; Other Senior Personnel: R. Ruchti, M. Wayne; Budget: $181K over 3 years]** proposes to build on its estensive expertise in scintillators and wavelength-shifting fibers, applying the results to optimize the designs that several other groups have proposed. Extensive testing of materials and readout schemes forms the core of the study. They also plan to test the idea of putting multiple cells on one readout fiber.

All of the groups interested in calorimetry also propose to carry out extensive simulation studies. The NIU group **[Project Leader: D. Chakraborty; Other Senior Personnel: G. Blazey, A. Maciel, V. Zutshi; Budget: $400K over 3 years]** has accepted the major responsibility of providing a GEANT4-based simulation package for use by all the detector groups. They have already developed a package that describes the American preliminary designs, adheres with the current input/output formats, and serves as the new standard for the ALCPG [5]. The group plans to add new features and combine the American package with the European standard into a single worldwide standard. They also cater to MC/simulation requests from the entire LC community. Development of PFAs is another key component of NIU's plans and they have made substantial early progress in this area. NIU's initiative in the sphere of software development for simulation and algorithms is large enough to justify its separation from their hardware efforts. The University of Chicago group puts a strong emphasis on MC studies and algorithm testing in order to optimize the physics reach of the detector subsystems. The Kansas group's proposal also takes advantage of simulations to assess their design for PFAs.

Major Calorimetry Milestones and Deliverables

In FY04, we will implement a particle flow algorithm. We will contribute to the design of a GEANT4-based simulation of the full LC detector. We will use GEANT4-based simulations to investigate segmentation for a Si-W or Si-W-scintillator ECal and to optimize the the cell and fiber configuration for a scintillator-based digital HCal. We will study RPC surface damage and gas mixtures, and design DAQ boards for the test beam study of a prototype RPC calorimeter.

In FY05, we will develop the design specifications for each technology passing the initial feasibility studies, will build prototype modules and design readout boards for beam tests. On the software front, we shall continue to refine algorithms and physics analyses using increasingly realistic and detailed detector simulation. We will report on the dependence of physics reach on calorimeter design and performance.

In FY06, we will complete a report with detailed side-by-side comparison of different technology options, taking into account cost, dependence on choices for other subsystems, and performance in terms of the ultimate physics reach. We will beam test prototype modules, and, for the selected technologies, will develop a full design taking into account mechanical issues and compatibility with other detector components. On the software side, we will develop a parametric simulation of the selected design and will port the full simulation to larger farms and the GRID network for the production of very large Monte Carlo samples.

6 Muon System

Muon systems will be important at the LC, not only for muon identification, but also to detect shower energy leaked from the hadronic calorimeter. The most promising muon system consists of planes of scintillator strips inserted in the gaps between iron plates [59] encircling the detector barrel.

The Notre Dame & NIU group **[Project Leader: M. Wayne (Notre Dame); Other Senior Personnel: G. Blazey, D. Chakraborty, D. Hedin, A. Maciel (NIU); Budget: $173K over 3 years]** will develop a C++/GEANT4 simulation of a preliminary muon system. The goal is to develop a flexible system that can be seamlessly integrated into the full LC detector simulation with easy variation of the detector parameters. Muon system reconstruction software would also be developed. NIU will also build a test stand for quality control of extruded scintillator plates containing wavelength-shifting fibers. The Notre Dame group will devise a fiber routing scheme and techniques for working with both clear and wavelength shifting fibers.

Major Muon Detector Milestones and Deliverables

In FY04, we will construct a GEANT4-based simulation of a preliminary muon system, and will develop a muon tracking system. We will also have extruded scintillator at a new facility commissioned jointly with Fermilab and devised a fiber routing scheme.

In FY05, we will provide studies of candidate muon systems and parameter choices and will have improved understanding of the performance as a function of strip length, width and placement, and will be able to characterize the performance of fibers.

In FY06, the simulation will become mature, and pre-production prototypes of counters suitable for test beams will be produced. We will also produce, test and install a prototype manifold with light guides for eight planes.

7 Education and Outreach Plan

We hope to share the excitement of high energy physics and the Linear Collider beyond the walls of the labs and universities.

To bring LC physics to high schools, we propose a new program of UCLC Fellows and UCLC Scholars. UCLC Fellowships will bring high school teachers to LC research, by providing funding for up to 8 weeks of summer research with UCLC groups. UCLC Scholarships will do the same for high school students. Fellows and Scholars will help build and test prototype detectors for beam monitors, vertex detectors, or the tracking, calorimetry and muon systems, working side-by-side with university physicists. For classroom transfer, teachers could take home, for example, cosmic ray detectors in the form of component parts so that their students could assemble and operate them.

Fellows and Scholars will be viewed as members of UCLC. We expect Fellows to attend the workshop of the American Linear Collider Physics Group during the summer of their Fellowship. In addition to attending the regular sessions of the Workshop, we envisage a special session at that workshop in which science teachers participating in LC research would present their results to one another. This session would include all UCLC Fellows, both from this detector program and from the partner UCLC accelerator program, as well as teachers participating in LC research through other programs such as Quarknet or RET. The UCLC Scholars from the detector and accelerator programs will also present their results to one another through a video forum near the end of the summer.

UCLC Fellows and Scholars will be selected competitively. Individual UCLC university groups will identify candidate Fellows through their contacts with local schools, or using contacts developed through Quarknet and RET programs. Fellows will be selected from among these candidates based on their qualifications and the appropriateness of the project proposed for them by the sponsoring university group. We expect that some UCLC Fellows will have participated in the very successful Quarknet or Research Experience for Teachers programs, but past participation in those programs is not a requirement. Similarly, UCLC Scholars will be drawn from the communities neighboring UCLC universities, and will be selected on the basis of recommendations by their teachers.

UCLC Fellows and Scholars will receive a stipend of $5000 and $1500 respectively and modest travel support on a case-by-case basis. In addition, teachers will receive $1000 support for classroom transfer materials and support for travel to the ALCPG workshop. We plan to support two Fellows and two Scholars in detector research in the first year of this program and four of each in the second and third years.

In addition to mentoring UCLC Fellows and Scholars, UCLC groups will continue their ongoing education and outreach activities. UCLC groups will engage numerous undergraduates in their research. Each year, at least 10 undergraduates will contribute to UCLC detector projects, either independently or through Research Experience for Undergraduates (REU) programs. Wherever possible, the LC will be introduced into outreach activities aimed at K-12 students and the general public.

8 Project Management Plan

Cornell University will be responsible for overall management of the activities of UCLC. Maury Tigner will serve as PI, with Mark Oreglia and Ritchie Patterson serving as co-PI's. Ritchie Patterson will also serve as Project Manager. Each project external to Cornell will be funded by a subcontract award from Cornell to the project leader's institution. For projects involving more than one university, the project leader's institution will award a "second tier" subcontract to the other institution.

Financial reports for each project will be assembled from the subcontracting universities and Cornell quarterly. The funding of each project will be tracked against the project's budget.

Each project leader will be expected to submit a written progress report to the Project Manager every six months. In addition, the project leader or his or her delegate will give an oral report at the summer meeting of the ALCPG. The progress will be tracked against the deliverables promised in the project description.

Annually, the work of UCLC and LCRD will be jointly reviewed by independent review panels under the auspices of the US Linear Collider Steering Group. The continuation of funding for each project at its nominal level will depend on the evaluation of the review panel, the completion of the promised deliverables, and the availability of funds.

The project leaders and UCLC management will meet annually at the summer ALCPG workshop to discuss matters of consortium-wide interest and policy. There will also be a meeting of UCLC and LCRD coordinators in conjunction with the ALCPG workshop.

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