A University Program of Accelerator and Detector Research for the International Linear Collider (vol. III)

FY 2005 – FY 2007

University Consortium for Linear Collider R&D

and

Linear Collider Research and Development Working Group

March 2, 2005

G.D. Gollin, editor

This document is available electronically at http://www.hep.uiuc.edu/LCRD/.

Executive Summary

In the last several years, the international high energy physics community has come to a consensus that the next large project should be a TeV-scale linear collider. In the U.S. this is evidenced by the consensus reached at the Snowmass 2001 workshop and the subsequent statement by HEPAP:

> We recommend that the highest priority of the U.S. 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 U.S. participation should be undertaken as a partnership between DOE and NSF, with the full involvement of the entire particle physics community....[*]

This document is part of an effort to pursue a large-scale, national program of research and development leading to the design of the International Linear Collider. It has been written by groups from a large number of universities in collaboration with national and industrial laboratories as well as foreign institutions. The proposed research is intended to extend the ongoing work being done at labs and universities around the world.

The large participation and spontaneous assembly of many groups to form this research program expresses both the high level of interest in the university community to participate in this work and the desire to work together in a coordinated fashion to accomplish a common, important goal.

The Department of Energy and the National Science Foundation are supportive of university participation in accelerator and detector projects for the ILC. From this document, which describes a coherent national research program in a fashion independent of funding source, are derived the proposals submitted to the agencies in 2002, 2003, and 2005.

The authors have worked closely with the American Linear Collider Physics Working Groups and the laboratories doing accelerator research to ensure that the most important issues were addressed.

Nearly half the proposed work is related to advancing accelerator technology. This is a change from the recent past when the vast majority of high energy physics R&D work performed at universities concerned detector development. In general, the critical path accelerator research needed for the International Linear Collider is already underway at

[*]DOE/NSF High Energy Physics Advisory Panel Subpanel On Long Range Planning For U.S. High Energy Physics, january 2002. Their report is available at http://doe-hep.hep.net/lrp_panel/.

the national laboratories. Some of the work proposed here supports these critical path items. However, most of the proposed projects concentrate on the next level of development: issues that must be resolved in order to build the ILC in a timely fashion, based on a solid design and reliable cost estimates.

There has been ongoing Linear Collider research and development work at laboratories and universities for the last twenty years. As the accelerator nears construction, more resources will be needed to finalize its design. The work proposed here will not only accomplish the short-term goals described above, but will also will train new scientists and engineers, contributing to the pool of talent and expertise that will be needed to accomplish the large task of building the International Linear Collider accelerator and detector.

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Introduction

A worldwide consensus that the next large facility in particle physics should be an international high energy electron-positron collider has emerged in the last several years. The strong recommendation from the U.S. High Energy Physics Advisory Panel that a high energy, high-luminosity, electron-positron linear collider be the highest priority of the U. S. program was paralleled in Europe and Asia. Each region recognized 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, and the necessity for international cooperation.

Response to this consensus has been swift. Regional Steering Committees, charged with organizing and coordinating Linear Collider activities in Asia, Europe, and the Americas, have been formed, as has their international counterpart, the International Linear Collider Steering Committee. Under the auspices of the ILCSC, technical reviews of the two competing collider technologies have been completed and an International Technology Recommendation Panel recommended the development of the superconducting design. At the national level, the U.S. Department of Energy announced inclusion of the Linear Collider in its 20 year plan for new facilities, according it highest priority among the mid-term projects under consideration.

The response from the U.S. High Energy Physics community has been equally swift. In early 2002, physicists from U.S. universities and laboratories organized a series of workshops at Chicago, Fermilab, Cornell, SLAC, and U.C. 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. The University Consortium for Linear Collider R&D (UCLC) organized itself to consider these issues in the context of NSF support, and the Linear Collider Research and Development Working Group (LCRD) did likewise in the context of DOE support. The two groups are naturally intermingled with each other, and with the preexisting American Linear Collider Physics Group (ALCPG). All concerned are working together to coordinate their activities to the single task of building the linear collider.

The result was the production of a joint UCLC/LCRD document, *A University Program of Accelerator and Detector Research for the Linear Collider***,** which collected the combined NSF and DOE proposals into a single program for LC related R&D. The Working Groups of the American Linear Collider Physics Group provided guidance, coordination, and advice to the individual proponents of both detector and accelerator R&D. They were joined by an *ad hoc* Accelerator Working Group that did the same for the accelerator proposals. In all, 71 proposals were collected from 47 U.S. universities, which addressed the full range of detector and machine/detector interface concerns, and complemented existing accelerator R&D efforts. A group of UCLC and LCRD organizers assembled a coherent document that was submitted for rigorous review to separate Detector and Accelerator Review Panels which met at Fermilab in

September, 2002. After allowing for minor changes in the sub-proposals in response to comments from the reviewers, the UCLC /LCRD organizers assembled the final document on October, 22, 2002, and then formally submitted it to the NSF and DOE. DOE funded the highest ranked detector R&D sub-proposals in March, 2003, and, after further internal review, the chosen accelerator proposals in May. Roughly $400k was allotted to each of detector and accelerator R&D. The NSF began funding the UCLC consortium with $150k in late Spring, with the understanding that the full proposal should be resubmitted for reconsideration early in the FY04 budget process.

The following year, Volume II of *A University Program of Accelerator and Detector Research for the Linear Collider*, presented the continuation of the Linear Collider R&D proposal process for FY04. As in year one, it described a nationally coordinated program of university based linear collider research reaching across both funding agencies. Forty-eight U.S. universities from 25 states, working with five national and industrial labs and eleven foreign institutions, wrote 68 proposals in a broad coverage of the previously identified R&D needs of the linear collider. Accelerator R&D maintained the prominent role it took in Volume I.

The present volume continues this program, describing the progress of projects that had received multiple-year funding, as well as presenting new proposals to the funding agencies. There are a variety of administrative differences in the proposal process this year: most notably that DOE and NSF are going to share a common panel of reviewers in order to increase the efficiency of the proposal process.

The agencies have asked that new proposals consider a three-year horizon. Within this time frame, key detector and accelerator R&D issues critical to the success of the Linear Collider will be addressed, and a growing community of high energy physicists will be initiated into the study of physics at the Linear Collider.

Physics Goals at the International Linear Collider

The physics goals of the Linear Collider are ambitious and compelling. The Linear Collider is needed to address the 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.

Although we do not know the mechanism of electroweak symmetry breaking, we have some good hypotheses. 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, we know this model does not work well 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. But 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, of course, but most realistic mechanisms we have imagined result in a Higgs boson or some related phenomena accessible to the Linear Collider.

The TeV scale is the natural place to look for the agents of electroweak symmetry breaking. Thus, the ongoing Run 2 at Fermilab's Tevatron has a chance of getting the first glimpses of these phenomena. 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 (LC) 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 LC can determine the lightest superpartners' masses with exquisite precision. Since the LHC measures mass differences more precisely than the masses themselves, one sees that a single LC measurement will significantly improve and extend the whole 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 Linear Collider is the right next step for experimental high energy physics, and now is the time to take it in order to maximize the interplay of its results with those of the LHC.

The full scientific case for the Linear Collider can be found in the Resource Book prepared for Snowmass 2001 or the physics chapter of the Tesla Technical Design Report. We believe the essential elements of the physics case have been made persuasively, and we are responding by banding together to meet the technical challenges that remain, so that the device can be built in a timely and cost-effective fashion.

The Need for Detector and Accelerator R&D for the Linear Collider

The physics goals of the Linear Collider require a starting energy of 500 GeV, upgradeable to 1 TeV or more and a luminosity of about 2×10^{34} cm^{-2} s^{-1}, an ambitious four orders of magnitude larger than the luminosity achieved by the first linear collider, the SLC. Achieving the high energy and ultra-low emittance of the Linear Collider requires significant advances in accelerator physics and technology: end-to-end simulation of the entire accelerator complex; mastery of the consequences of strong wakes; ultra-fast beam manipulation; nanometer stability of the beams at the crossing point; extreme stability in beam energy, luminosity and polarization; handling unprecedented beam power; and the development of instrumentation to monitor the beam on a bunch-by-bunch basis. A construction start in 2010 requires that the basic R&D

required for a full technical design be complete by 2006. Much R&D remains to be done, and is urgently needed. The International Linear Collider Technical Review Committee concluded its 2003 report with a list of high priority R&D items in the areas of: accelerator simulation and design; accelerator experiments; the development and test of radio-frequency systems, instrumentation, and other hardware; and operational issues.

To exploit the full physics potential of a 500 GeV Linear Collider, the detector must move well beyond the designs of the LEP/SLC era, and beyond the current state of the art. The detector development which has gone on in preparation for the LHC experiments has certainly advanced the art, particularly in terms of extreme rate capability and radiation hardness, and also in terms of dealing with the TeV energy scale in tracking and calorimetry. But it has not pushed detector performance to the level *required* for high precision measurements at the LC, or to the level *allowed* by the very different experimental environment found at the LC: low event rates, a relatively benign radiation field, and events clean from the debris of the underlying event or multiple interactions.

R&D is required for each of the major detector subsystems. High performance vertex detection is a necessity at the LC, to extract the full precision from measurements of the Higgs branching fractions into *b* quarks, *c* quarks, and gluons. Development is needed to boost CCD readout speeds and radiation hardness and/or to develop fast, thin, high resolution alternatives. Very high momentum resolution in the tracking detector, which will permit the Higgs to be tagged in recoil with a *Z*, will require new readout techniques and improved spatial resolution in the TPC, or precision alignment in a silicon tracker. Further studies are needed to guarantee full coverage in the forward region, to study backgrounds and thinning requirements and evaluate pattern recognition capabilities for different designs. LC calorimeters must distinguish *W* and *Z* bosons, and improve energy resolution by a factor of two over today's designs. Energy flow calorimetry must be fully simulated and detector parameters optimized. Since lepton ID involves the interplay of the tracking detector and both the electromagnetic and hadronic calorimeters, overall system performance must be evaluated and optimized. The case for hadron ID, besides its obvious application for quark flavor tagging in Giga-*Z* running, hasn't yet been made, so it needs further study. Precision threshold measurements will depend on a determination of the machine energy to an accuracy well beyond what has been so far achieved and precise knowledge of the differential luminosity spectrum, a new variable at colliders.

University Participation in Accelerator and Detector Research and Development

The community of High Energy Physics experimentalists, as well as other members of the scientific community, can bring expertise and a fresh perspective to many of these problems. The engagement of HEP experimentalists in accelerator physics has often played an important role in the development of new accelerator technologies, and was an essential part of the development of the SLC. The machine/detector interface grew less distinct as particle physicists learned to measure beam sizes from deflection scans and beam energies with synchrotron light, and came to play a significant role in developing accelerator controls and instrumentation, fast kicker magnets, and beamstrahlung monitors. Many of the most fundamental experimental challenges in studying high energy e^+e^- collisions reside with the accelerator, so it is natural to direct part of the intellectual resources of the HEP community in this direction.

The design, construction, and utilization of the Linear Collider 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 LCRD/UCLC proposal marks a fundamental change in the level of engagement of U.S. universities in the Linear Collider (LC). In the year 2001, LC work was supported at fifteen U.S. universities, and the work was largely confined to physics and detector simulation studies. Almost all of the accelerator-related work was performed at national laboratories. In this proposal, the number of institutions has increased by almost a factor of four, with most participants having had no prior affiliation with the any LC effort. The detector sub-proposals request support to move beyond simulation, into prototyping of real devices. In a significant broadening of focus, nearly half of the sub-proposals are for work on accelerator issues. The increase in numbers and breadth of focus follows on the Snowmass consensus, and the excitement and commitment of the U.S. university physics community toward making the Linear Collider a reality.

One of the organizing principles of this proposal is that the task of designing and building the collider and detectors contains, *a priori*, hundreds of research and development issues that are excellent fits to the mission and resources of university physics and engineering groups. Although critical path issues are already under investigation at the major laboratories, many important technical issues remain unaddressed and unresolved. Solutions to these problems will yield essential instrumentation for the Linear Collider, reduce its cost, increase its reliability, and contribute to the selection of optimal technologies. University–laboratory collaborations will disseminate knowledge of the issues, bring fresh perspectives, and perhaps lead to breakthroughs.

The study and control of dense beams of electrons requires a scientific and engineering infrastructure that starts in electrodynamics and beam physics, but spills into many other fields, including lasers, optics, interferometry, motion stabilization, superconductivity, materials science, acoustics, plasma physics, microwaves, and power and control systems. Problems in these areas are ideal foci for interdisciplinary collaborations with other university departments beyond physics, which can build a support base for the Linear Collider, and fulfill its potential as a broad stimulant for all science and technology. Some of this collaboration-across-boundaries has already been realized in the research projects presented here, and we expect to see more of it arise as the work progresses.

We wish to stress that universities bring a very important resource to any research and development program: students. In engaging our graduates and undergraduates, we serve to train the next generation of scientists and engineers in all of the fields described above. Our students participate as more than just a skilled and enthusiastic labor pool: when the facility is operating, many of these student "builders" will have become members of the next generation of high energy physicists. Their research will be conducted simultaneously at the Collider facility and in the academic departments of every collaborating institution, carrying forth the excitement and stimulation of science and technology into the larger community.

Structure of the Document and Coordination Between LCRD and UCLC

This document has been written in collaboration by members of LCRD and UCLC, and describes the combined set of research projects that members of both groups are planning to pursue. We have found it most natural to organize the research around the topics to be studied, and this is reflected in the order in which projects appear in the body of *A University Program of Accelerator and Detector Research for the International Linear Collider (vol. III).*

The material is divided into sections covering accelerator physics and technology; luminosity, energy, and polarization measurements; vertex detectors; tracking detectors; calorimetry; muon system. Each section begins with a brief overview of some of the technical issues, followed by descriptions of the R&D projects written by the participating groups. Appendices at the end of the document provide additional information about the level of total funding requested.

One of our concerns was to develop an effective set of projects with easy collaboration across the boundaries of geography and funding agency in order to avoid unnecessary, and inefficient duplication of effort. We have been aided greatly in this by the ALCPG and its working group leaders, capably led by Jim Brau and Mark Oreglia. To balance the ALCPG's focus on detector issues, Tom Himel, Joe Rogers, and Dave Finley formed The American Working Group on Linear Collider Accelerator Technology in order to play a similar role in the accelerator physics sphere. Shekhar Mishra stepped in after Joe's untimely death in 2004, assuming even larger obligations concerning the ILC than before. They have all done us a significant service. We have found that the combination of shared goals, common sense, and the excitement of beginning something new have made the process go remarkably smoothly.

The U.S. Linear Collider Steering Group, chaired by Jonathan Dorfan, has played a significant role in coordinating the review and submission process for the proposals. After negotiating a sensible timeline and review process with the funding agencies and participants, the Steering Group assembled the review panels, received their reports, and provided guidance on the dissemination of results to proponents. The Steering Group continues to provide guidance concerning direction and organization to both UCLC and LCRD.

Budgets shown in this document are expected to reflect accurately the ultimate budgets submitted to the funding agencies. For UCLC project descriptions the budget tables are identical to those used to generate the UCLC proposal transmitted to NSF. However, LCRD subproposal budgets have not yet been reviewed by the various offices of sponsored research at the proponents' home institutions. It is possible that further scrutiny of the algorithms governing calculation of indirect costs will necessitate minor corrections to some of the LCRD subproposal budgets.

The greatest part of the work associated with the generation of the proposals has come from the participating groups. The present set of organizers (from both LCRD and UCLC) who have been working to smooth the way for the proponents are listed below.

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