A University Program of Accelerator and Detector Research for the Linear Collider

University Consortium for Linear Collider R&D

and

Linear Collider Research and Development Working Group

October 22, 2002

This document is available electronically at http://www.hep.uiuc.edu/LCRD/html_files/proposal.html. It has been modified since the preliminary draft was posted.

The preliminary draft, released for review September 6, 2002, can also be found at http://www.hep.uiuc.edu/LCRD/html_files/proposal.html.

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 embark on a large-scale, national program of research and development leading to the design of a high energy linear electron-positron collider. It has been written by groups from 47 universities in 22 different states (in collaboration with six national and industrial laboratories, and eleven foreign institutions). The proposed research is intended to extend the ongoing work being done at labs and universities around the world. It comprises 71 different research projects which are requesting support at the level of $2.3M in the first year of what will evolve into a multi-year program.

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.

Both the Department of Energy and the National Science Foundation are interested in funding linear collider research and development. For administrative reasons, it is necessary to submit separate proposals in different formats to the agencies. From this document, which describes a coherent national research program in a fashion independent of funding source, will be derived the pair of proposals to be submitted simultaneously to the agencies in October, 2002. The separate proposals will be submitted to the NSF and DOE by the University Consortium for Linear Collider R&D (UCLC) and the Linear Collider Research and Development Working Group (LCRD) respectively. UCLC and LCRD have closely coordinated their work to produce a single research plan which will later be split into its component parts for submission to the agencies.

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*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 authors have worked closely with the preexisting 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 Linear Collider is already underway at 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 Linear Collider 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 Linear Collider accelerator and detector.

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Introduction

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 U.S. High Energy Physics Advisory Panel (HEPAP) called for vigorous U.S. participation in a Linear Collider effort:

> 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.
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> 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....[*]

Response to this consensus has been 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.

This document unites the information of LCRD and UCLC proposals, presenting a first model of a single, nationally coordinated program of university based linear collider research. Forty-seven U.S. universities from 22 states, working with six national and industrial labs and eleven foreign institutions, offer 71 proposals in a broad coverage of

[*] DOE/NSF High Energy Physics Advisory Sub-panel on Long Range Planning for U.S. High Energy Physics, Jan. 2002, http://doe-hep.hep.net/lrp_panel/.

the previously identified R&D needs of the linear collider.[†‡] Significant attention to accelerator R&D (almost half of the proposals) is especially notable, and reverses the recent trend away from accelerator physics in many U.S. physics departments. The large participation and spontaneous assembly of this broad proposal expresses the high level of interest in university groups, their excitement about the physics to be done, and their conviction that the Linear Collider represents the future of the field. The physics goals of the Linear Collider are ambitious and compelling!

Physics at the Frontier

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

[†] J. Brau et al., "International Study on Linear Collider R&D", http://blueox.uoregon.edu/~lc/randd.pdf, and also "The Detector List", http://blueox.uoregon.edu/~jimbrau/LC/rdpriorities.
[‡] T. Himel et al. "The Accelerator List" , http://www-project.slac.stanford.edu/lc/Project_List/intro.htm.

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.

This is not the place to repeat the full scientific case for the linear collider. For further reading, one can consult 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.

Design Requirements on the Accelerator and Detector and the Need for R&D

The physics case for the Linear Collider requires a starting 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. However, it is widely recognized that achieving such performance presents a significant challenge to the accelerator builders. Consequently, the accelerator community is welcoming help in solving the technical problems before it. Acceleration gradients must be increased in order to reach the TeV energy goal cost effectively; improved beam monitoring and instrumentation (and much more) must be developed to achieve the desired luminosity; better schemes for positron production need to be explored; techniques for positron polarization must be further investigated.

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.

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 LC physics or adapted to 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. These measurements will test the defining properties of the Higgs and may point the way to the fundamental parameters of SUSY. The low duty cycle and low event rates at the LC may allow the use of detector technologies with comparatively long readout times but very high resolution and segmentation, like CCDs. Development is needed to boost readout speeds and radiation hardness, and to thin the detectors. Very high momentum resolution in the tracking detector will permit the Higgs to be tagged in recoil with a *Z* by measuring the dilepton decay of the *Z* with great accuracy. Good momentum resolution will also pinpoint the masses of SUSY particles by precisely determining the endpoints of the box spectra of their decay products. The momentum resolution required, $\Delta p/p \sim 5 \times 10^{-5}$, is more than an order of magnitude better than that achieved in the LEP detectors, and will require improved spatial resolution and control of systematics in a TPC, or precision alignment in a silicon tracker. Accurate tracking must extend over the full solid angle in order to boost the efficiency for measuring multi-jet final states; and the forward tracking elements must deliver 0.1mr angular resolution to measure the differential luminosity spectrum. Discriminating *W* and *Z* bosons will be essential in studies of Higgs couplings and strong *WW* and *ZZ* scattering. To do so on the basis of jet-jet invariant masses will require the jet energy resolution in the calorimeter to be twice as good as that achieved today. The proposed solution, generically called energy flow calorimetry, needs to be much better understood at the simulation level before the parameters of a realistic detector can be optimized. Calorimeter expense will likely dominate the detector total cost, adding to the impetus to develop practical hardware solutions for energy flow calorimetry. Lepton ID will remain a critical tool for LC physics studies. 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.

University Participation in Accelerator and Detector Research and Development

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, almost 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 Linear Collider.*

The material is divided into sections covering accelerator physics and technology; luminosity, energy, and polarization measurements; vertex detectors; tracking detectors; calorimetry; muon and particle identification systems. Each section begins with a table of contents and an overview of the planned investigations, 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 and the geographical distribution of the participants.

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. They have all done us a significant service, reviewing early versions of project descriptions to suggest cooperation between groups, changes of focus, and adjustment of priorities. We have found that the combination of shared goals, common sense, and the excitement of beginning something new have made the process go more smoothly than anticipated.

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.

The original draft of this document was released for review to a pair of committees on September 6, 2002. One, chaired by Norbert Holtkamp (ORNL), evaluated the proposed accelerator physics projects while the other, chaired by Howard Gordon (BNL), reviewed proposed detector R&D. Comments and rankings from the committees were distributed to contact persons in late September and will be reported to the funding agencies by the Steering Group. As had been discussed at the Santa Cruz *Linear Collider Retreat* in June, proponents were given an opportunity to respond to the review panels.

In response to the reviews, nine LCRD subproposals have been modified by the proponents, while three have been withdrawn. Generally, the modifications are minor, involving changes in budget, scope, or emphasis. Some of the modifications consist only of explanatory comments meant to clarify points already addressed in the original subproposals. In this document, changes to LCRD projects are described in short notes placed immediately before the original (September 6) version. As a result, both the note and the original proposal must be taken together as a description of the proposed work.

Several of the UCLC project descriptions have been revised in response to reviews while four have been withdrawn. (Many of the UCLC budgets have been corrected to conform to the methods governing calculation of indirect costs and subcontracting expenses.) In a format which differs slightly from that used by LCRD, these changes are documented in introductory sections contained in the (revised) project descriptions. Though the original project descriptions are not presented after the revised, final versions, they are still available on the UCLC web site (http://www.lns.cornell.edu/public/LC/UCLC/) and the combined proposal document site (http://www.hep.uiuc.edu/LCRD/html_files/proposal.html).

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.

It is our hope that the methods of presentation of revisions will preserve the utility and integrity of the reviews of the September drafts. The design of the revision process was guided and constrained by the goal of reacting to the reviews in a way that makes this possible. Thus the majority of the proposals have not been revised.

The landscape is evolving rapidly. The HEPAP recommendation concerning the Linear Collider was released in January, 2002. Nine months later, after workshops at Chicago, Fermilab, Cornell, SLAC, and Santa Cruz, the physics community in the United States has generated a set of 71 research proposals to participate in the realization of a new machine. It is an exciting time.

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

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