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

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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.[*]

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 fifty universities (in collaboration with six national and industrial laboratories, and seven foreign institutions). The proposed research is intended to extend the ongoing work being done at labs and universities around the world. It comprises 77 different research projects which are requesting support at the level of $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.[*]

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. Fifty U.S. universities, working with six national and industrial labs and eight foreign institutions, offer seventy-seven proposals in a broad coverage of the previously identified R&D needs of the linear collider.[†‡] Significant attention to accelerator R&D

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[*] 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/.

[†] 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.

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(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 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

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[‡] T. Himel et al. "The Accelerator List" , http://www-project.slac.stanford.edu/lc/Project_List/intro.htm.

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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

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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

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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.

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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 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 seventy-seven 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.

Dan Amidei (amidei@umich.edu)	Michigan
Gerry Dugan (gfd1@cornell.edu)	Cornell
George Gollin (g-gollin@uiuc.edu)	Illinois
John Jaros (john@slac.stanford.edu)	SLAC
Andreas Kronfeld (ask@fnal.gov)	Fermilab
Usha Mallik (usha-mallik@uiowa.edu)	Iowa
Ritchie Patterson (ritchie@mail.lns.cornell.edu)	Cornell
Joe Rogers (jtr1@cornell.edu)	Cornell

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Appendices and References

Appendix 1: Participation Data for the LCRD and UCLC Proposal

Profiles of requested funding

LCRD	$FY2003	proposals
Accelerator Physics	$732,082	23
Luminosity, Energy, Polarization	$112,541	7
Vertex Detector	$73,000	2
Tracking	$149,948	6
Calorimetry	$308,690	7
Muon system and Particle Identification	$92,810	2
Total	$1,469,071	47

UCLC	$FY2003	$FY2004	$FY2005	Total	proposals
Accelerator Physics	$639,460	$1,121,628	$1,051,709	$2,812,797	14
Luminosity, Energy, Polarization	$62,000	$245,000	$252,000	$559,000	2
Vertex Detector	$113,050	$126,400	$248,550	$488,000	2
Tracking	$278,500	$545,700	$630,100	$1,454,300	6
Calorimetry	$225,320	$527,135	$857,062	$1,609,517	5
Muon system and Particle Identification	$46,200	$56,100	$57,000	$159,300	1
Total	$1,364,530	$2,621,963	$3,096,421	$7,082,914	30

LCRD + UCLC	$FY2003	proposals
Accelerator Physics	$1,371,542	37
Luminosity, Energy, Polarization	$174,541	9
Vertex Detector	$186,050	4
Tracking	$428,448	12
Calorimetry	$534,010	12
Muon system and Particle Identification	$139,010	3
Total	$2,833,601	77

Profiles of institutional participation

LCRD + UCLC	institutions	personnel
Universities	50	217
National and industrial laboratories	6	75
Foreign institutions	8	11

Geographical distributions for participants

Shown in the maps are the numbers of times a research group based in a particular state appears in the collaboration list for a subproposal submitted to LCRD or UCLC. Groups from national labs in New York (BNL), Illinois (ANL and Fermilab), and California (LBNL and SLAC) are included in the upper figure (and center column of the table), but not in the lower map.

CA	28	9
CO	3	3
CT	6	6
HI	1	1
IA	8	8
IL	32	18
IN	11	11
KS	1	1
LA	1	1
MA	7	7
MI	10	10
MN	1	1
NC	3	3
NJ	1	1
NM	1	1
NY	10	10
OH	2	2
OK	2	2
OR	3	3
PA	1	1
SC	3	3
TN	3	3
TX	6	6
VA	1	1
WI	1	1

Participation level in Linear Collider R&D projects, including national labs

32 to 32 (1)
28 to 32 (1)
11 to 28 (1)
10 to 11 (2)
8 to 10 (1)
7 to 8 (1)
6 to 7 (2)
3 to 6 (5)
2 to 3 (2)
1 to 2 (9)
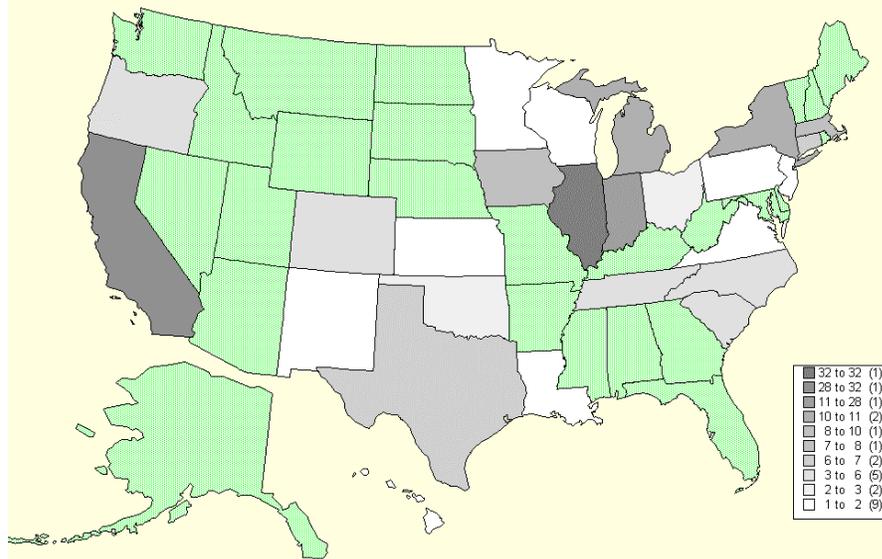
Participation level in Linear Collider R&D projects, not including national labs

18 to 18 (1)
11 to 18 (1)
10 to 11 (2)
9 to 10 (1)
8 to 9 (1)
7 to 8 (1)
6 to 7 (2)
3 to 6 (5)
2 to 3 (2)
1 to 2 (9)
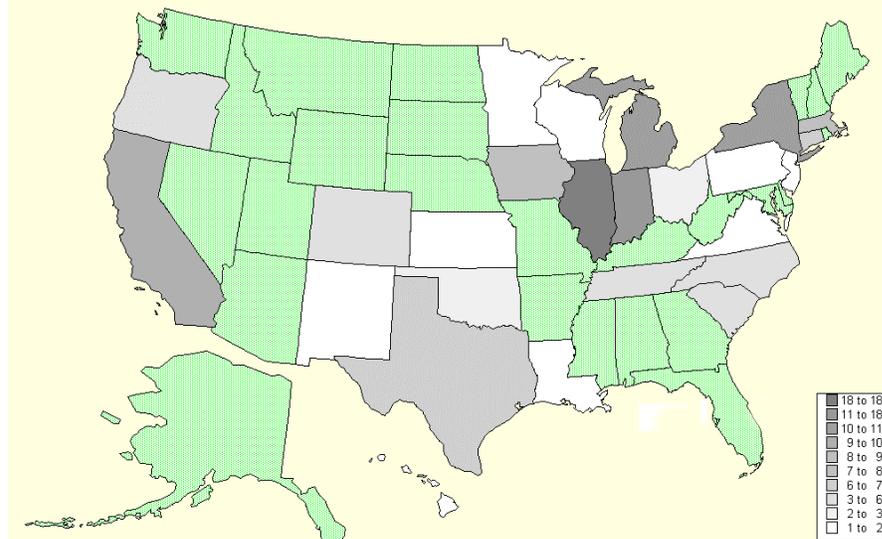
Summary data for submitted proposals

LCRD	2.1.Beam Halo Monitor		
accelerator	Lucien Cremaldi	cremaldi@phy.olemiss.edu	(662) 915-5311
Collaborating institutions: Mississippi			
Requested support: FY 2003: $30,001 FY 2004: $0 FY 2005: $0			

LCRD	2.2.Beam Test Proposal of an Optical Diffraction Radiation Beam Size Monitor at the SLAC FFTB		
accelerator	Yasuo Fukui	fukui@slac.stanford.edu	(650) 926-2146
Collaborating institutions: UCLA SLAC			
Requested support: FY 2003: $46,000 FY 2004: $0 FY 2005: $0			

LCRD	2.3.Design and Fabrication of a Radiation-Hard 500-MHz Digitizer Using Deep Submicron Technology		
accelerator	K.K. Gan	gan@mps.ohio-state.edu	(614) 292-4124
Collaborating institutions: Ohio State SLAC			
Requested support: FY 2003: $43,400 FY 2004: $0 FY 2005: $0			

LCRD	2.4.RF Beam Position Monitor for Measuring Beam Tilt		
accelerator	Young-Kee Kim	ykkim@lbl.gov	(630) 840-2405
Collaborating institutions: UC Berkeley Berlin LBNL Notre Dame SLAC			
Requested support: FY 2003: $37,000 FY 2004: $0 FY 2005: $0			

UCLC	2.5.Non-intercepting electron beam size diagnosis using diffraction radiation from a slit		
accelerator	Bibo Feng	bibo.feng@vanderbilt.edu	(615) 343-6446
Collaborating institutions: Vanderbilt			
Requested support: FY 2003: $36,600 FY 2004: $74,500 FY 2005: $88,500			

UCLC	2.6.Single-shot, electro-optic measurement of a picosecond electron bunch length		
accelerator	Bill Gabella	b.gabella@vanderbilt.edu	(615) 343-2713
Collaborating institutions: Vanderbilt			
Requested support: FY 2003: $77,500 FY 2004: $104,000 FY 2005: $64,000			

UCLC	2.7.Fast Synchrotron Radiation Imaging System for Beam Size Monitoring		
accelerator	Jim Alexander	jima@lns.cornell.edu	(607) 255-5259
Collaborating institutions: Albany Cornell			
Requested support: FY 2003: $27,000 FY 2004: $43,000 FY 2005: $27,000			

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LCRD	2.8.Machine Serviceable Electronics Standards		
accelerator	Michael Haney	m-haney@uiuc.edu	(217) 244-6425
Collaborating institutions: Illinois LBNL Rice			
Requested support: FY 2003: $9,240 FY 2004: $0 FY 2005: $0			

LCRD	2.9.Radiation damage studies of materials and electronic devices using hadrons		
accelerator	David Pellett	pellett@physics.ucdavis.edu	(530) 752-1783
Collaborating institutions: UC Davis Fermilab SLAC			
Requested support: FY 2003: $19,180 FY 2004: $0 FY 2005: $0			

UCLC	2.10.BACKGAMMMON: A Scheme for Compton backscattered photoproduction at the Linear Collider		
accelerator	S. Mtingwa	mtingwa@mit.edu	(336) 334-7423
Collaborating institutions: NCA&T			
Requested support: FY 2003: $39,000 FY 2004: $43,000 FY 2005: $47,000			

LCRD	2.11.Ground Motion studies versus depth		
accelerator	Mayda Velasco	mvelasco@lotus.phys.nwu.edu	(847) 467-7099
Collaborating institutions: Fermilab Northwestern SLAC			
Requested support: FY 2003: $19,819 FY 2004: $0 FY 2005: $0			

LCRD	2.12.Investigation of Linear Collider Control System Requirements and Architecture		
accelerator	Gerry Abrams	GSAbrams@lbl.gov	(510) 486-7188
Collaborating institutions: LBNL SLAC			
Requested support: FY 2003: $0 FY 2004: $0 FY 2005: $0			

UCLC	2.14.Investigation of GAN Techniques in the Development and Operation of the TTF Data Acquisition System		
accelerator	Don Hartill	dlh@lns62.cornell.edu	(607) 255-8787
Collaborating institutions: Cornell Ohio State			
Requested support: FY 2003: $28,900 FY 2004: $48,900 FY 2005: $60,800			

LCRD	2.15.Investigation of acoustic localization of rf cavity breakdown		
accelerator	George Gollin	g-gollin@uiuc.edu	(217) 333-4451
Collaborating institutions: Illinois SLAC			
Requested support: FY 2003: $9,032 FY 2004: $0 FY 2005: $0			

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LCRD	2.16.Investigation of Breakdown in 17 GHz Accelerator Structures		
accelerator	Michael Shapiro	shapiro@psfc.mit.edu	(617) 253-8656
Collaborating institutions: MIT SLAC			
Requested support: FY 2003: $40,000 FY 2004: $0 FY 2005: $0			

LCRD	2.17.RF Cavity Diagnostics, Design, and Acoustic Emission Tests		
accelerator	Lucien Cremaldi	cremaldi@phy.olemiss.edu	(662) 915-5311
Collaborating institutions: Mississippi			
Requested support: FY 2003: $23,480 FY 2004: $0 FY 2005: $0			

LCRD	2.18.Control of Beam Loss in High-Repetition Rate High-Power PPM Klystrons		
accelerator	Mark Hess	mhess@psfc.mit.edu	(617) 253-8454
Collaborating institutions: MIT Mission Research Corp			
Requested support: FY 2003: $40,000 FY 2004: $0 FY 2005: $0			

LCRD	2.19.Nonlinear electrodynamic response of RF superconducting cavities		
accelerator	Alex Gurevich	agourevi@facstaff.wisc.edu	(608) 263-2549
Collaborating institutions: Wisconsin			
Requested support: FY 2003: $60,000 FY 2004: $0 FY 2005: $0			

UCLC	2.20.Research in Superconducting Radiofrequency Systems		
accelerator	H. Padamsee	hsp3@cornell.edu	(607) 255-5727
Collaborating institutions: Cornell			
Requested support: FY 2003: $30,000 FY 2004: $65,000 FY 2005: $90,000			

UCLC	2.21.RF Breakdown Experiments at 34 Ghz		
accelerator	J.L. Hirshfield	jay.hirshfield@yale.edu	(203) 432-5428
Collaborating institutions: Yale			
Requested support: FY 2003: $58,200 FY 2004: $154,400 FY 2005: $147,600			

LCRD	2.22.Investigation of Novel Schemes for Injection/Extraction Kickers		
accelerator	George Gollin	g-gollin@uiuc.edu	(217) 333-4451
Collaborating institutions: Cornell Fermilab Illinois			
Requested support: FY 2003: $2,362 FY 2004: $0 FY 2005: $0			

LCRD	2.23.Ring-tuned, permanent magnet-based Halbach quadrupole		
accelerator	James Rosenzweig	rosen@physics.ucla.edu	(310) 206-4541
Collaborating institutions: UCLA Fermilab			
Requested support: FY 2003: $36,950 FY 2004: $0 FY 2005: $0			

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LCRD	2.24.Radiation Damage to Permanent Magnets	
accelerator	Lucien Cremaldi cremaldi@phy.olemiss.edu	(662) 915-5311
Collaborating institutions: Mississippi		
Requested support: FY 2003: $14,990 FY 2004: $0 FY 2005: $0		

UCLC	2.25.Investigation and prototyping of fast kicker options for the TESLA damping rings	
accelerator	Gerry Dugan gfd1@cornell.edu	(607) 255-5744
Collaborating institutions: Cornell		
Requested support: FY 2003: $2,000 FY 2004: $121,000 FY 2005: $67,000		

LCRD	2.26.Proposal to Test and Revise Designs for Linac and Final Doublet Component Movers	
accelerator	David Warner Warner@lamar.colostate.edu	(970) 491-1035
Collaborating institutions: Colorado State SLAC		
Requested support: FY 2003: $50,000 FY 2004: $0 FY 2005: $0		

LCRD	2.27.Coherent Synchrotron Radiation	
accelerator	James Ellison ellison@math.unm.edu	(505) 277-4613
Collaborating institutions: New Mexico		
Requested support: FY 2003: $20,000 FY 2004: $0 FY 2005: $0		

LCRD	2.28.Simulation Study of Source Issues for the Linear Collider	
accelerator	Dan Amidei amidei@umich.edu	(734) 764-3266
Collaborating institutions: UCLA Fermilab Michigan SLAC		
Requested support: FY 2003: $80,500 FY 2004: $0 FY 2005: $0		

UCLC	2.29.Improved simulation codes and diagnostics for high-brightness electron beams	
accelerator	Courtlandt L. Bohn cbohn@fnal.gov	(815) 753-6473
Collaborating institutions: NIU		
Requested support: FY 2003: $62,960 FY 2004: $56,428 FY 2005: $58,809		

UCLC	2.30.Beam simulation: main beam transport in the linacs and beam delivery systems, beam halo modeling and transport, and implementation as a diagnostic tool for commissioning and operation	
accelerator	Dave Rubin dlr@cesr10.lns.cornell.edu	(607) 255-3765
Collaborating institutions: Cornell		
Requested support: FY 2003: $14,000 FY 2004: $19,000 FY 2005: $30,000		

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UCLC	2.31.Simulation of Nonlinear Beam Dynamics and Interconnection to Beam Monitoring Subsystems		
accelerator	Martin Berz	berz@msu.edu	(517) 355-6446
Collaborating institutions: Illinois Michigan State			
Requested support: FY 2003: $46,000 FY 2004: $145,000 FY 2005: $158,000			

UCLC	2.32.Damping ring studies for the LC		
accelerator	S. Mtingwa	mtingwa@mit.edu	(336) 334-7423
Collaborating institutions: NCA&T			
Requested support: FY 2003: $46,000 FY 2004: $52,000 FY 2005: $57,000			

LCRD	2.33.A Compact Wakefield Measurement Facility		
accelerator	Kwang-Je Kim	kwangje@aps.anl.gov	(630) 252-4647
Collaborating institutions: Argonne Chicago Fermilab			
Requested support: FY 2003: $70,000 FY 2004: $0 FY 2005: $0			

UCLC	2.34.Experimental, simulation, and design studies for linear collider damping rings		
accelerator	Joe Rogers	jtr1@cornell.edu	(607) 255-4093
Collaborating institutions: Cornell Minnesota			
Requested support: FY 2003: $66,200 FY 2004: $106,700 FY 2005: $40,200			

LCRD	2.35.Flat beam generation in Photocathode		
accelerator	Shyh-Yuan Lee	shylee@indiana.edu	(812) 855-7637
Collaborating institutions: Fermilab Indiana LBNL			
Requested support: FY 2003: $20,689 FY 2004: $0 FY 2005: $0			

LCRD	2.36.Advanced Beam Manipulations with RF quadrupoles		
accelerator	Shyh-Yuan Lee	shylee@indiana.edu	(812) 855-7637
Collaborating institutions: Argonne Indiana			
Requested support: FY 2003: $20,689 FY 2004: $0 FY 2005: $0			

LCRD	2.37.Study of Polarized Positron Production for the LC		
accelerator	William Bugg	bugg@slac.stanford.edu	(865) 974-7799
Collaborating institutions: South Carolina SLAC Tennessee Princeton			
Requested support: FY 2003: $38,750 FY 2004: $0 FY 2005: $0			

UCLC	2.38.Development of Superconducting Helical Undulators for Positron Production		
accelerator	Kwang-Je Kim	kwangje@aps.anl.gov	(630) 252-4647
Collaborating institutions: Chicago			
Requested support: FY 2003: $105,100 FY 2004: $88,700 FY 2005: $115,800			

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LCRD	3.1.A Fast Gas Cerenkov Calorimeter for Bunch-by-Bunch Luminosity Measurement at the Next Linear Collider	
LEP	John Hauptman	hauptman@iastate.edu	(515) 294-8572
Collaborating institutions: Iowa State SLAC Texas Tech		
Requested support: FY 2003: $16,000 FY 2004: $0 FY 2005: $0		

LCRD	3.2.R&D for luminosity monitor	
LEP	Yasar Onel	yasar-onel@uiowa.edu	(319) 335-1853
Collaborating institutions: Fairfield Iowa		
Requested support: FY 2003: $0 FY 2004: $0 FY 2005: $0		

LCRD	3.3.Energy Spectrometer Design Study for the Linear Collider Extraction Line	
LEP	Stan Hertzbach	hertzbach@physics.umass.edu	(650) 926-2507
Collaborating institutions: U Mass.		
Requested support: FY 2003: $20,125 FY 2004: $0 FY 2005: $0		

LCRD	3.4.Quartz fiber Cerenkov detector for precision beam energy spectrometer	
LEP	Eric Torrence	torrence@physics.uoregon.edu	(541) 346-4618
Collaborating institutions: Oregon		
Requested support: FY 2003: $14,899 FY 2004: $0 FY 2005: $0		

UCLC	3.5.A Demonstration of the Electronic and Mechanical Stability of a BPM-Based Energy Spectrometer for an e+e- Linear Collider	
LEP	Mike Hildreth	mikeh@ undhep.hep.nd.edu	(574) 631-6458
Collaborating institutions: Notre Dame		
Requested support: FY 2003: $54,000 FY 2004: $155,000 FY 2005: $153,000		

LCRD	3.6.Polarimetry at LC	
LEP	Yasar Onel	yasar-onel@uiowa.edu	(319) 335-1853
Collaborating institutions: Fairfield Iowa Iowa State		
Requested support: FY 2003: $10,000 FY 2004: $0 FY 2005: $0		

LCRD	3.7.Compton polarimeter backgrounds	
LEP	William Oliver	william.oliver@tufts.edu	(617) 627-5364
Collaborating institutions: Tufts		
Requested support: FY 2003: $28,000 FY 2004: $0 FY 2005: $0		

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UCLC	3.8.Beam-beam collision monitoring using Large Angle Beamstrahlung		
LEP	Giovanni Bonvicini	giovanni@physics.wayne.edu	(313) 577-1444
Collaborating institutions: Wayne State			
Requested support: FY 2003: $8,000 FY 2004: $90,000 FY 2005: $99,000			

LCRD	3.9.Development of thin, fast, radiation hard, 3d-electrode array, silicon radiation sensors		
LEP	Sherwood Parker	sher@slac.stanford.edu	(510) 841 2012
Collaborating institutions: Hawaii			
Requested support: FY 2003: $23,517 FY 2004: $0 FY 2005: $0			

LCRD	4.1.A Proposal for R&D on CCD Vertex Detectors for Future Linear e+ e- Colliders		
vertexing	Charlie Baltay	baltay@yalph2.physics.yale.edu	(203) 432-3386
Collaborating institutions: Oregon Yale			
Requested support: FY 2003: $50,000 FY 2004: $0 FY 2005: $0			

UCLC	4.2.Development and design of an LC ASIC for CCD readout and data reduction		
vertexing	Patrick Skubic	pls@mail.nhn.ou.edu	(405) 325-3961
Collaborating institutions: Boston University Oklahoma			
Requested support: FY 2003: $73,700 FY 2004: $86,400 FY 2005: $95,300			

UCLC	4.3.Study of the Mechanical Behavior of Thin silicon and the Development of hybrid silicon pixels for the LC		
vertexing	Daniella Bortoletto	daniella@physics.purdue.edu	(765) 494-5197
Collaborating institutions: Purdue			
Requested support: FY 2003: $39,350 FY 2004: $40,000 FY 2005: $153,250			

LCRD	4.4.Investigation of new technologies for the silicon vertex tracker		
vertexing	David Buchholz	dbuchholz@nwu.edu	(847) 491 5454
Collaborating institutions: Fermilab Northwestern			
Requested support: FY 2003: $23,000 FY 2004: $0 FY 2005: $0			

LCRD	5.1.Development and Testing Linear Collider Forward Tracking		
tracking	Michael Strauss	mgstrauss@ou.edu	(405) 325-3961
Collaborating institutions: Oklahoma			
Requested support: FY 2003: $41,708 FY 2004: $0 FY 2005: $0			

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LCRD	5.2.Evaluation of a GEM based Forward Tracking Prototype for the NLC		
tracking	Lee Sawyer	sawyer@phys.latech.edu	(318) 251-2407
Collaborating institutions: Louisiana Tech			
Requested support: FY 2003: $37,490 FY 2004: $0 FY 2005: $0			

UCLC	5.3.Straw Tube Wire Chambers for Forward Tracking in the Linear Collider Detector		
tracking	Keith Baker	baker@jlab.org	(757) 727-5820
Collaborating institutions: Hampton			
Requested support: FY 2003: $32,500 FY 2004: $95,700 FY 2005: $100,100			

LCRD	5.4.Fabrication and investigation of Gas Electron Multipliers for charged particle tracking		
tracking	Peter Fisher	fisherp@mit.edu	(617) 253-8561
Collaborating institutions: MIT NCA&T			
Requested support: FY 2003: $0 FY 2004: $0 FY 2005: $0			

LCRD	5.5.Studies of the Use of Scintillating Fibers for an Intermediate Tracker which Provides Precise Timing and Bunch Identification		
tracking	Rick VanKooten	rvankoot@indiana.edu	(812) 855-2650
Collaborating institutions: Fermilab Indiana Notre Dame			
Requested support: FY 2003: $39,500 FY 2004: $0 FY 2005: $0			

UCLC	5.6.Application of CLEO tracking to a TPC		
tracking	Dan Peterson	pls@lns.cornell.edu	(607) 255-8784
Collaborating institutions: Cornell			
Requested support: FY 2003: $7,000 FY 2004: $4,000 FY 2005: $4,000			

UCLC	5.7.Tracking Detector R&D at Cornell and Purdue Universities		
tracking	Dan Peterson	dpp@lns.cornell.edu	(607) 255-8784
Collaborating institutions: Cornell Purdue			
Requested support: FY 2003: $80,000 FY 2004: $149,000 FY 2005: $102,000			

UCLC	5.8.Tracking simulation studies and alignment system R&D		
tracking	Keith Riles	kriles@umich.edu	(734) 764-4652
Collaborating institutions: Michigan			
Requested support: FY 2003: $45,000 FY 2004: $88,000 FY 2005: $129,000			

LCRD	5.9.Tracking Software Optimization for the Silicon Detector Option		
tracking	Milind Purohit	purohit@beauty.physics.sc.edu	(803) 777-6996
Collaborating institutions: South Carolina			
Requested support: FY 2003: $31,250 FY 2004: $0 FY 2005: $0			

LCRD	5.10.Use of Silicon Strip Detectors in Low Duty-Cycle Applications	
tracking	Bruce Schumm	schumm@scipp.ucsc.edu	(831)-459-3034
Collaborating institutions: UC Santa Cruz		
Requested support: FY 2003: $0 FY 2004: $0 FY 2005: $0		

UCLC	5.11.R&D towards a Silicon drift detector based main tracker for the NLC-SD option	
tracking	Rene Bellwied	bellwied@physics.wayne.edu	(313) 577-5407
Collaborating institutions: Wayne State		
Requested support: FY 2003: $82,000 FY 2004: $174,000 FY 2005: $202,000		

UCLC	5.12.Negative Ion TPC as the NLC main tracker	
tracking	Giovanni Bonvicini	giovanni@physics.wayne.edu	(313 577-1444)
Collaborating institutions: Temple Wayne State		
Requested support: FY 2003: $32,000 FY 2004: $35,000 FY 2005: $93,000		

UCLC	6.1.Design and Prototyping of a Scintillator-based Digital Hadron Calorimeter	
calorimetry	Vishnu Zutshi	zutshi@fnal.gov	(630) 840-5764
Collaborating institutions: NIU Illinois-Chicago		
Requested support: FY 2003: $71,510 FY 2004: $158,490 FY 2005: $287,040		

LCRD	6.2.Linear Collider Detector Development Proposal to Study and Develop Scintillator-Fiber Readout Scintillator Calorimetry with High Spatial Resolution	
calorimetry	Uriel Nauenberg	uriel@pizero.colorado.edu	(303) 492-7715
Collaborating institutions: Colorado		
Requested support: FY 2003: $54,484 FY 2004: $0 FY 2005: $0		

UCLC	6.3.Fast Response Tile Scintillation Development for Calorimetry and Tracking in NLC Detectors	
calorimetry	Dan Karmgard	karmgard.1@nd.edu	(574) 631-3362
Collaborating institutions: Notre Dame		
Requested support: FY 2003: $44,410 FY 2004: $46,145 FY 2005: $78,322		

LCRD	6.4.Exploring Crystal Calorimetry for A Linear Collider Detector	
calorimetry	Usha Mallik	usha-mallik@uiowa.edu	(319) 335-0499
Collaborating institutions: Caltech Iowa South Carolina SLAC UT Austin		
Requested support: FY 2003: $53,805 FY 2004: $0 FY 2005: $0		

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LCRD	6.5.Development of a silicon-tungsten test module for an electromagnetic calorimeter		
calorimetry	Raymond Frey	rayfrey@cosmic.uoregon.edu	(541) 346-5873
Collaborating institutions: Oregon SLAC			
Requested support: FY 2003: $37,500 FY 2004: $0 FY 2005: $0			

LCRD	6.6.Digital Hadron Calorimetry for the Linear Collider using GEM technology		
calorimetry	Andy White	awhite@uta.edu	(817) 272-2812
Collaborating institutions: Argonne Northern Illinois UT Arlington			
Requested support: FY 2003: $72,641 FY 2004: $0 FY 2005: $0			

UCLC	6.9.Development of energy-flow algorithms, simulation, and other software for the LC detector		
calorimetry	Dhiman Chakraborty	dhiman@fnal.gov	(630) 840-8569
Collaborating institutions: NIU			
Requested support: FY 2003: $45,400 FY 2004: $96,500 FY 2005: $144,700			

UCLC	6.10.Investigation and Design Optimization of a Compact Sampling Electro-magnetic Calorimeter with High Spatial, Timing and Energy Resolution		
calorimetry	Graham Wilson	gwwilson@ku.edu	(785) 864-5231
Collaborating institutions: Kansas			
Requested support: FY 2003: $49,000 FY 2004: $124,000 FY 2005: $195,000			

UCLC	6.11.Optimization of LC detector elements for physics analysis		
calorimetry	Mark Oreglia	m-oreglia@uchicago	(773) 702-7446
Collaborating institutions: Chicago			
Requested support: FY 2003: $15,000 FY 2004: $102,000 FY 2005: $152,000			

LCRD	6.12.Micro-machined Vacuum Photodetectors		
calorimetry	Yasar Onel	yasar-onel@uiowa.edu	(319) 335-1853
Collaborating institutions: Fairfield Iowa			
Requested support: FY 2003: $0 FY 2004: $0 FY 2005: $0			

LCRD	6.13.Cherenkov compensated calorimetry		
calorimetry	Yasar Onel	yasar-onel@uiowa.edu	(319) 335-1853
Collaborating institutions: Fairfield Iowa Iowa State			
Requested support: FY 2003: $40,160 FY 2004: $0 FY 2005: $0			

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LCRD	6.14.Study of Resistive Plate Chambers as Active Medium for the HCAL		
calorimetry	José Repond	repond@hep.anl.gov	(630) 252-7554
Collaborating institutions: Argonne Boston University Chicago Illinois			
Requested support: FY 2003: $50,100 FY 2004: $0 FY 2005: $0			

LCRD	7.2.Scintillator Based Muon System R&D		
muons	Paul Karchin	karchin@physics.wayne.edu	(313) 577-5424
Collaborating institutions: UC Davis Fermilab Northern Illinois Notre Dame Rice Wayne State UT Austin			
Requested support: FY 2003: $57,710 FY 2004: $0 FY 2005: $0			

UCLC	7.3.Scintillator Based Muon System R&D		
muons	Arthur Maciel	maciel@fnal.gov	(630) 840-8314
Collaborating institutions: NIU Notre Dame			
Requested support: FY 2003: $46,200 FY 2004: $56,100 FY 2005: $57,000			

LCRD	7.4.Particle Identification and Software Infrastructure for Linear Collider Physics and Detector Studies		
muons	Robert Wilson	wilson@lamar.colostate.edu	(970) 491-5033
Collaborating institutions: Colorado State SLAC			
Requested support: FY 2003: $35,100 FY 2004: $0 FY 2005: $0			

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Appendix 2: *Linear Collider R&D*

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Linear Collider Detector R&D

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1   Introduction

There is now global consensus in the high energy community that the next accelerator project in particle physics needs to be an electron-positron linear collider (LC) with an energy range from $\sqrt{s} = M_Z$ up to about 1 TeV. The physics goals of the LC will profit from advances now in the detector technology to optimize the outcome of the experiments. Improvements include reducing systematics to the lowest level in order to take advantage of the high luminosity for precision measurements and providing the best possible efficiency for rare processes with high jet multiplicity. This document describes the current status of efforts around the world to design detectors capable of meeting these demands.

Several requirements exceed the current state-of-the-art in detectors as will be seen below. To address this, physics and detector studies are ongoing in Asia [1, 2], Europe [3, 4, 5] and North America [6, 7], and are co-operating within a world-wide study [8]. The co-chairs of the world-wide study [9] have suggested the compilation of this note to describe the detector R&D envisaged for the timely construction of a detector with the required performance, to list the R&D efforts presently pursued, and to point out the areas where efforts are missing or inadequately covered. Even as this note is being written, new efforts are being planned. Those which have not yet started are not included in this report, but will be listed on a web page [10] as they begin.

The purpose of this compilation is to help organise the R&D efforts more globally and to facilitate and foster interregional collaborations. This note is not meant to be prescriptive or exhaustive. There might well be useful detector R&D ideas that have not yet been considered. We also expect and encourage ideas on novel detector techniques. Explicitly included in considerations here are software developments in the context of the specific R&D efforts. We do not consider, however, generic software R&D which is mandatory but beyond the scope of this document.

Although a huge effort has been invested in detector development for the LHC program [11], with many benefits to other areas in high energy physics, there are nevertheless significant additional and different detector R&D challenges for the LC program. The principal challenges at the LHC are related to the high event rate and the high radiation levels associated with the pp energies and luminosities required to do physics with the parton component of the proton. Both of these problems are dramatically reduced at the LC where the 'bare partons', the electrons and positrons, are accelerated/collided directly, allowing competitive physics to be done with lower beam energies. This and the falling e^+e^- point-like total cross section are in contrast to the higher beam energy and approximately energy-independent total cross section in pp collisions. The freedom from these problems at first sight might suggest that the LC detector performance is easily achieved, but extensive studies since LCWS91 [12] have motivated a very challenging detector which goes beyond the possibilities with current technology. The primary new requirements are unprecedented hermeticity, track-momentum resolution, jet-energy resolution and flavour identification for b and charm jets. The importance of these issues is expanded upon in the next section. Briefly, the goals of the R&D programme include the following striking enhancements

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with respect to detectors at the LHC:

- 3–6 times closer inner vertex layer to the IP (higher vertexing precision),

- 30 times smaller vertex detector pixel sizes (improved position resolution and two-track resolution),

- 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, enabling sophisticated energy flow algorithms.

These advantages can be obtained since the readout speed and radiation hardness requirements at the LC are significantly relaxed relative to the LHC. But detector R&D is needed now to achieve the performance goals and to prepare for an optimal physics programme at the linear collider. Furthermore, with a detector R&D programme, one can expect new technologies to be developed, improving further the detector performance.

This document is structured as follows: In Section 2 the required performance of the detector or detector parts is given, followed by a short description of the detector designs under consideration or proposed within the regional studies, together with their similarities and differences. Section 3 lists the R&D efforts presently underway for the individual detector parts, and indicates some areas where additional effort should be invested. Section 4 describes the test beam issues.

2   Detector Performance Requirements

2.1   Physics Considerations for Detector Design

The anticipated physics program at an e^+e^- linear collider encompasses the wide range of centre-of-mass energies $\sqrt{s}$ from M_Z to about 1 TeV and a broad range of physics goals, from discovery to high precision measurements. The implications for the detector has been the subject of many studies and reports [1]-[13] as explained in the introduction. Extracting from those studies some physics benchmarks that make stringent demands on the detector design are listed in the following for illustration.

- Track momentum and angular resolution.
  Very good track momentum resolution is required to study a number of physical processes. Examples include the model independent measurement of the Higgs

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boson mass and ZH couplings through the reaction $e^+e^- \to ZH \to \ell^+\ell^- X$ or the determination of new-particle masses in cascade processes as in supersymmetry (SUSY), $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\ell^- \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ from the end-points of lepton spectra.

Because a number of proposed new physics processes have strong t-channel contributions and because some standard model (SM) topologies (W^+W^-, ZZ, $t\bar{t}$) cover the full solid angle, it will be important to maintain good momentum resolution at very forward angles, which will ensure reliable charge sign determination and jet measurement. In addition, the presence of beamstrahlung demands a differential beam luminosity measurement when scanning over particle thresholds (*e.g.*, W^+W^-, $t\bar{t}$, SUSY thresholds) to determine their masses and widths. The most accurate method known for differential luminosity measurement requires precisely measuring the angle between the outgoing electron and positron in low-angle Bhabha scattering [14].

- Vertex resolution.
  Flavor tagging derived from an excellent vertex detector is essential for many physics goals, in particular Higgs physics. For example, the determination of the branching ratios of the Higgs to fermions and bosons is dependent upon the performance of the vertex detector. In particular, the measurement of the coupling to charm in the presence of a much larger bottom coupling challenges even the best vertex detector.

  The typical events in the high energy regime will consist of multi-jet final states, and one will be obliged, due to small cross sections and hence small event samples, to extract the maximum possible information from these samples. For example, the high energy production of $t\bar{t}$, $t\bar{t}H$ or ZZH generally results in at least 6 jets, two or more being b-flavored, and possibly another two being charm jets. Identifying these jet flavors will be valuable in reducing combinatorial and other backgrounds.

  The vertex detector will be important in other cases, where not all the heavy particles decay hadronically. For example, in high energy W production, important physics can be extracted from events in which one W decays leptonically and the other to $c\bar{s}$, by efficient and pure idenfitication of the charm jet.

  In SUSY models, there can be HA final states in which each of the heavy Higgs particles decays to $t\bar{t}$ giving rise to complex 12-jet events. In these and many other crucially important processes, the capabilities of the vertex detector will be pushed to the limit. The measurement of vertex charge will take on great importance in reducing combinatorial backgrounds. Such physics scenarios drive the vertex detector design to be highly granular, with the best possible spatial resolution, extremely thin layers and an inner layer as close as possible to the interaction point.

- Energy-flow measurement.
  Many signatures from known processes and from new physics are expected to be

found in jets of hadronic final states; intermediate states must be detected in cascade decays to identify these processes and to efficiently suppress backgrounds. A key benchmark is the reconstruction of two jet decays of the W and the Z and the clean separation of these two gauge bosons. The energy-flow technique [1] combines the information from tracking and calorimetry to obtain the best possible estimate of the flow of jet particles and of the original four-momenta of the partons. Therefore excellent 3-D granularity is required also in the calorimetric detectors.

- Hermeticity.
  Determination of missing energy requires a detector without dead zones and with minimal opening along the beamline. The detector parts at the smallest polar angles have to be radiation hard with short sampling and readout times to avoid event pile-up for calorimetric measurements in that environment which has high backgrounds due to beam-beam effects.

- Machine environment.
  There are several machine-related issues [16] which influence detector design and performance.

  - Background.
    The background conditions per bunch crossing (BX) for the various subdetector parts are to first order independent of the different machine designs. The effects arising from beamstrahlung and associated e^+e^- pairs at the interaction point (IP) give rise to neutron and photon fluxes in the tracking volume and calorimeter. These are of particular importance and constraints on the choice of technologies can be expected.

  - Bunch time structure.
    The bunch time structure is rather different between the cold and warm technologies and requires different sampling and readout times. Therefore the R&D should take these differences into account. For example these have an impact on the number of BX a subdetector sees and the amount of background to expect. The bunch time structure will also determine the hardware needed for stabilisation of the final quadrupole doublet, which could affect significantly the detector design and hermeticity. Furthermore, pile-up of $e^+e^- \rightarrow e^+e^- hadrons$ (two-photon) events will create different issues for the two technologies.

  - Crossing angle.
    Because of bunch spacing the crossing angle of the two beams are different for the warm (8–20 mrad) and cold (head-on) technologies, the backgrounds

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[1]In the past the term "energy flow" has been used for different techniques, so there is potential for confusion. Here the term refers to the ability to follow charged tracks into and inside the calorimeter to subtract charged-track deposits from the calorimeter signals before combining tracking and calorimetry information. See also Section 3.2.

expected at the inner subdetectors might be different and this will have implications for the R&D requirements.

2.2   Detector Goals

The generic e^+e^- detector is composed of a tracking system (vertex, main and intermediate/forward tracker), calorimeter (electromagnetic and hadronic), coil, instrumented flux return yoke (or muon detector), and forward calorimeters. Some main performance goals resulting from the past three years of world-wide studies [1, 5, 6, 8] are

- for vertexing resolution: $\delta(IP_{r\phi,z}) \leq 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}\,\mathrm{GeV/c}}{p\sin^{3/2}\theta}$,

- for central tracking resolution: $\delta(\frac{1}{p_t}) \leq 5 \times 10^{-5}(\mathrm{GeV/c})^{-1}$ with systematic alignment uncertainties $\leq 10\,\mu\mathrm{m}$ for a TPC or $\leq 1\,\mu\mathrm{m}$ for a silicon tracker in the barrel region,

- for forward tracking resolution: $\delta(\frac{1}{p_t}) \leq 3 \times 10^{-4}(\mathrm{GeV/c})^{-1}$ and $\delta\theta \leq 2 \times 10^{-5}\mathrm{rad}$ for $|\cos\theta| \leq 0.99$,

- for jet energy resolution: $\frac{\delta E}{E} \simeq 0.30\,\frac{1}{\sqrt{E(\mathrm{GeV})}}$ from energy flow, from which follows that both electromagnetic and hadron calorimetry be inside the coil,

- for hermeticity: excellent forward coverage with the beam pipe as the only small ($\stackrel{<}{\sim}$ 5-10 mrad) hole in the 4π acceptance, and

- for robustness in the presence of background: minimal material inside the electromagnetic calorimeter, fine granularity in all subdetectors and a strong ($\geq$ 3T) $\vec{B}$-field.

3   R&D Activities

This section contains a compendium of different technologies presently under consideration for a detector at the linear collider, together with the R&D issues and the projects which are ongoing or being planned at the moment. No discussion of the different overall designs nor their respective advantages or disadvantages is given. An attempt is made to be as complete as possible and to indicate areas where information is still missing. Where specific details are given, they should be viewed as illustrative and not optimized.

3.1   Tracking System

All tracking system designs under consideration include a pixelated vertex detector that closely surrounds the interaction point for accurate measurement of charged particle impact parameters. Accurate momentum measurement is provided by either a

large-volume gas drift chamber (axial/stereo wires or time projection chamber) or additional silicon tracking layers (silicon drift detector or microstrips) immersed in axial magnetic fields of magnitude ≥ 3.0 T. Most designs also include a dedicated system of forward-tracking silicon disks at low angles. For the gas chamber barrel trackers, additional special silicon, straw-tube chamber or scintillating fiber layers are also under consideration for improving pattern recognition, momentum resolution, or timing precision.

3.1.1   Vertex Detector

Accelerator backgrounds dictate the minimum radius at which the first layer of the vertex detector can be placed. The two backgrounds of most concern are Bethe-Heitler electron-positron pairs created by radiation from the incident beams and the neutron backsplash from masks downstream of the interaction point. The first can create unacceptable occupancy and is directly affected by the strength of the detector's solenoidal field. The second is a source of radiation damage, with a nominal expected annual dose of $\sim 10^9$ neutrons/cm^2. Uncertainties in background calculations are large, however, making it desirable to be able to withstand much higher rates without significant performance deterioration.

Traditionally there has been a tradeoff in pixelated detectors among intrinsic spatial resolution, readout speed, radiation hardness, and material thickness (which degrades impact parameter resolution at low momenta). Readout speed is most critical in the TESLA accelerator design where integrated particle occupancy in the first vertex detector layer over a full bunch train (950 μs) would approach 4% without the improvements being planned. In the following, brief descriptions are given of ongoing detector R&D related to a variety of pixel technologies.

Charge Coupled Devices (CCDs)

The CCD vertex subdetector [17] of the SLD detector has shown the power of CCD technology in a low-duty-cycle accelerator such as the LC. CCDs offer demonstrated intrinsic spatial resolution below 5 μm and potentially very low material thickness since active regions are of $\mathcal{O}(20\mu\text{m})^3$ with readout proceeding directly through the bulk. Their disadvantages include slow readout speed and modest radiation hardness. Three collaborations are actively pursuing R&D to develop CCD technology for a linear collider detector. The LCFI (Linear Collider Flavour Identification) Collaboration [18, 19], consisting of six U.K. institutes (Bristol, Lancaster, Liverpool, Oxford, Queen Mary-Univ. of London, RAL); a U.S. collaboration [20] (Oregon, Yale); and a Japanese collaboration [1] (KEK, Niigata, Tohoku, Toyama) are working in parallel on some or all of the following issues:

- thinning the silicon bulk to a minimum, with a goal of achieving a ladder thickness of $\sim 0.1\% X_0$,

- prototyping a mechanical support based on tension ("stretched CCDs"),

- manufacturing detectors which are more radiation hardened and developing techniques for coping with radiation (e.g., charge injection to fill traps),

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- developing higher readout clock speed, parallel-column readout and greater integration of readout electronics, and

- developing CCD operation at near room temperature.

<u>Active Pixel Sensors</u>

Two types of Active Pixel Sensors (APS) devices are receiving scrutiny as alternatives to CCD vertex detectors. Hybrid devices (HAPS) [21, 22] are being studied by a European collaboration (CERN, Helsinki, INFN, Krakow, Warsaw) where work is underway to reduce material thickness and improve spatial resolution through smaller pitch and interleaved readout exploiting capacitive charge division, by analogy with the use of this procedure for microstrip detectors.

Monolithic Active Pixel Sensors (MAPS), an approach based on CMOS technology, offers intrinsic spatial resolution comparable to CCDs with the advantage of avoiding charge transfer through the bulk, of better radiation hardness and of room-temperature operability. The primary R&D goals are to produce large devices with the readout speed, noise performance and thin substrates required for the LC vertex detector. The work is at present being done primarily by a European collaboration (IReS, LEPSI, RAL, U. of Liverpool, U. of Glasgow, U. of Geneva, and NIKHEF) [23, 24].

Another new technology [25] involves the DEPFET (depleted FET) concept [26], which is being pioneered as a pixel detector by a collaboration of Bonn University and MPI Munich. In this device, the charge storage takes place in a buried channel below the conducting layer of a surface-channel MOSFET. The standard (top) gate is held at fixed potential and the transistor current is modulated by the charge in the 'internal gate'. Readout is by off-detector CMOS circuits, presumably to be attached by bump-bonding as for the CCD option.

In general, the bump-bonding technology (pixel sensors to CMOS, CCDs to CMOS, CMOS to CCDs, CMOS to CMOS) is exploding commercially as well as for scientific sensors, and is opening up a number of exciting opportunities for the LC vertex detector.

3.1.2   Main Tracker

Excellent track reconstruction efficiency and momentum resolution are desirable over a large solid angle at the linear collider. Two distinct approaches are under consideration for the barrel tracking system: a large-volume gas drift chamber (axial/stereo wire or time projection), with many coarse measurements, and a silicon tracker with a few precise measurements per track. Technical tradeoffs are being investigated within each of these approaches. There are also global tradeoffs among them, pertaining to pattern recognition, robustness against background, material budget affecting multiple scattering, bunch discrimination via timing, and interface to calorimetry. Collaborative simulation work (Colorado, Michigan, Indiana, Santa Cruz, Wayne State) [27] is pursued by the North American community to address these global issues. Below is a summary of ongoing detector R&D for each of the barrel tracker technologies considered.

<u>Jet Chamber</u>

The Asian detector design includes an option for a large-volume drift chamber (radius 2.3 m, half-length 2.3 m) with axial and small-angle stereo wires. A long-term R&D program [1, 28] is well underway at KEK, TUAT, and Kinki University, to address the following issues:

- controlling / monitoring wire sag,

- maintaining uniform spatial resolution (85 μm) over tracking volume,

- maintaining good 2-track resolution (< 2 mm),

- stable operation of stereo cells,

- gas gain saturation (affects dE/dx, 2-track separation),

- Lorentz angle effect on cell design,

- wire tension relaxation (Al wires),

- gas mixture, and

- coping with neutron backgrounds.

<u>Time Projection Chamber</u>

The European and American detector designs include a large-volume time projection chamber (TPC) (radius 1.7 to 2 m, half-length ca. 2.5 m). A collaboration [29] of European (Aachen, DESY/Hamburg, Karlsruhe, Kraków, MPI-Munich, NIKHEF, Novosibirsk, Orsay/Saclay, Rostock) and North American Institutes (Carleton/Montreal/Victoria, LBNL, MIT) has begun a comprehensive R&D program to address the following topics.

- Novel readout schemes to improve two-hit and point resolution, and reduce ion feedback. Technologies considered at the moment are GEM [30] and MicroMEGAS [31], which should allow for good intrinsic suppression of ion feedback. A method derived from silicon technology is also being studied. The wire-chamber alternative with high granularity [5] is being considered as a backup to and benchmark for the new technologies.

- Electronics integration to cope with $\mathcal{O}(3 \cdot 10^6)$ or more readout pads and high-speed sampling ($\sim$20 MHz or more) to exploit intrinsic longitudinal granularity, or ($\sim$100 MHz or more) to exploit induced signals on neighboring pads.

- Spatial resolution smaller than 100μm ($\sim$ 2$\times$ better than at LEP).

- Readout channel reduction via optimized pad shaping/ganging with attention to 2-track and dE/dx resolution.

- Optimized gas mixture for resolution, drift speed, sensitivity to backgrounds, ageing and implications for the field cage.

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- Mechanical design to minimize material in field cages and endcaps, while providing adequate cooling for high-density electronics.

- Alignment correction techniques for coping with space charge buildup.

- Calibration schemes.

- Detailed technical simulations of readout designs with comparison to measurement of prototype devices.

<u>Silicon Tracker</u>

Various study groups are also considering in their simulations, in addition to the TPC described above, a 5-layer silicon barrel tracker of maximum outer radius 1.25 m and maximum half-length 1.67 m. Two different silicon technologies are under consideration: silicon drift detector and silicon microstrips, discussed below.

Silicon drift detectors are being studied by the Wayne State group [27, 32]. Detailed simulations of a silicon drift detector design for the LC have begun and the group advocates investigating the following issues in an R&D program.

- Development of thinner substrates and necessary mechanical support.

- Improved spatial resolution (to better than 10μm in both dimensions).

- Increased drift length to reduce front end electronics (FEE) in the fiducial volume.

- Lower mass FEE readout.

Silicon microstrip detectors are being studied by a collaboration of UC-Santa Cruz, SLAC, Colorado, Tokyo, MIT and LPNHE Paris [27, 33]. The collaboration has begun detailed simulations of a silicon microstrip detector design and is initiating an R&D program to address the following:

- develop long ladder using existing 'Viking' chip or other ASIC technologies,

- power cycling to avoid need for active cooling,

- optimized shaping time for signal/noise, given the low expected radiation dose,

- nearest-neighbor readout for pulse centroid-finding,

- electronics of thin (less than 300μm) detectors,

- incorporation of both minimum ionizing and $1/\beta^2$ analog regimes, and

- Lorentz angle considerations.

It has been suggested that the mechanical rigidity requirements of the silicon trackers (drift or microstrips) could be eased by the use of an alignment monitoring system modelled on the ATLAS detector's chirped interferometer scheme [34], allowing for less support material in the tracker's fiducial volume.

3.1.3   Forward and Intermediate Trackers

Most of the tracking system designs include a set of silicon annuli (discs) providing angular coverage to $|\cos\theta| \sim 0.99$. In the TESLA TDR design, the first three (of seven) disc layers from the interaction point are active pixel sensors; the rest are silicon microstrips, as are all of the annuli in the LC detector designs under study in North America. The design of the forward discs in the JLC detector design is open. While silicon-based designs are getting most of the attention, other solutions need to be thoroughly examined.

The UC-Santa Cruz/SLAC collaboration [33] working on barrel silicon microstrip R&D also plans to develop simulation infrastructure for basic studies. In Korea, Kyungpook National University, Ewha Womans University, and Korea University are developing microstrip detectors for intermediate tracking and are preparing for a beamtest [35].

Both of the European and North American TPC designs also include a barrel silicon layer just inside the inner radius of the TPC. The extra layer provides improved momentum resolution and provides improved pattern recognition to match tracks across the gap between the vertex detector and the gas chamber. The R&D being carried out or proposed by the LPNHE-Paris [36], Santa Cruz, SLAC, and Wayne State (silicon drift) groups for other silicon layers is expected to be relevant to this intermediate layer also.

The LPNHE-Paris group has also proposed [36] to insert large silicon annular planes behind the endplate of the European TPC and a large barrel layer beyond the outer radius of the TPC, in both cases between the tracking chamber and the electromagnetic calorimeter. Together with the internal Si-microstrip layers, this ensemble of Si-trackers would constitute a Si-envelope to the TPC [37], the necessity of which is being studied. The endcap tracking layer improves momentum resolution at forward angles, and the outer barrel layer offers a precise calibration point for the gas chamber, along with precise track extrapolation into the calorimeter. The issues for these detectors have much in common with the central tracking silicon detectors described above, and collaborative R&D is underway. Given the sizes of these auxiliary tracking layers, lowering manufacturing cost will be important R&D goals.

A DESY group has proposed a superlayer of straw drift chambers behind the endcap of the European TPC, mainly to improve momentum resolution at small angles [14, 15]. Technical R&D issues include spatial resolution, material thickness, timing for bunch tagging, and calorimeter and mask splashback.

An Indiana group [27] is investigating the timing advantages of a superlayer of scintillating fibers in place or adjacent to the intermediate barrel silicon layer in the North American TPC option. R&D issues include timing precision and material thickness.

3.2   Calorimeter

In addition to the traditional functions of calorimeters - namely, measurement of individual electromagnetic and hadronic showers - a LC calorimeter system should provide the means of reconstructing jet four-momenta. It is now broadly assumed that this will

be done through an energy-flow algorithm (EFA). The EFAs rely on the measurement of momenta of charged particles in jets using the tracking system, the energy of photons and electrons using the electromagnetic calorimeter, and the energy of neutral hadrons (K_L^0, n) from both the electromagnetic and hadronic calorimeters. The algorithms depend critically on the ability of separating the different components among the energy deposits in the calorimeter which in turn implies following the charged particles into the calorimeter. This requires high granularity (both longitudinal and transverse) in order to avoid double counting of charged and neutral energies as demonstrated at LEP/SLC/HERA and to assign appropriate weights in the calorimetry for software compensation; it will be verified by studies of EFAs for different types of calorimeters. The development of optimal EFAs is a significant area for R&D on its own. The optimization of weights for electromagnetic and hadronic components may also be accomplished by hardware compensation. These studies are in progress as part of ongoing hardware projects or as explicit simulation studies [38].

In addition, the muon system must provide some calorimetry to detect leakage out of the calorimeter proper, and a forward system of calorimeters is needed to complete hermetic coverage and provide a luminosity measurement based on small angle Bhabha scattering.

3.2.1   Electromagnetic Calorimeter (ECAL)

The ECAL is required to measure electromagnetic showers with good energy resolution, of order $10\%/\sqrt{E}$, and to be finely segmented to allow for the separation of the various components of jets. Several concepts are presently being evaluated:

a) *Silicon-Tungsten Sandwich Calorimeter.*
The SiW calorimeter provides the highest granularity (~ 1 cm^2) combined with a very small Moliere radius. Currently, the CALICE collaboration [15, 39] and U. of Oregon/SLAC [40] are pursuing the SiW option. The areas of R&D include production and quality control of tungsten plates, design of the silicon detectors, front-end readout chip and detector mechanics.

b) *Tile-Fibre calorimeter.*
The Tile-Fibre calorimeters presently under study allow less granularity in the range of 3×3cm^2 to 5×5cm^2, but the cost is significantly lower than that of the SiW option. Efforts are going on in Asia (KEK, Kobe U., Konan U., Niigata U., Shinshu U., and Tsukuba U.) [41, 42] and in Europe (Padova, Como, Trieste, Frascati) [15, 43]. Particular emphasis lies on the study of tile sizes and the configuration of fibres.

In order to supplement the granularity, shower-max detector layer(s) with a finer granularity may be added. Shinshu U. and Konan U. [44] are studying scintillator strip arrays as a shower max detector where photon detectors are directly attached on the strips, and silicon pad arrays are being studied [43].

The use of scintillator with different decay times for the front and back parts of the calorimeter in a shaslik-type detector is also a studied option as described in [15].

c) *Other Options for ECAL.*
Scintillating crystals provide excellent energy resolutions particularly for low energy

photons even though longitudinal segmentation is difficult to implement and the cost tends to be high. A crystal option for ECAL is being studied at Caltech [45]. Also, scintillator strip arrays are being investigated for a full electromagnetic calorimeter by Kobe U. and Tsukuba U [46].

3.2.2 Hadron Calorimeter (HCAL)

All designs of hadron calorimeters presently under investigation are based on the concept of the sandwich calorimeter with either iron or lead plates as absorber. Several options for the active medium are being explored world-wide.

a) *Tile-Fibre calorimeters.*
One candidate for HCAL is the tile-fibre calorimeter where the segmentation is coarser than that of the ECAL. One criterion for the absorber material is the effective interaction length which includes the effect of the transverse shower spread in the scintillator gaps. Iron is advantageous in this respect. Lead has a shorter interaction length and is known to give hardware compensation at a lead/tile ratio of around 4mm/1mm. Investigations within the CALICE collaboration [39] include the mechanical design, study of tile sizes and fibre routing and, in particular, the read-out system. Hardware compensation is under investigation at KEK, Kobe U., Konan U., Shinshu U., and Tsukuba U. [47].

b) *Digital calorimeter.*
High granularity can be achieved with a so-called digital calorimeter where only the hit pattern is read out and no pulse-height information is used. Several aspects of this concept are being pursued by the CALICE collaboration [39] and institutions in North America (Northern Illinois U., ANL, and U. of Utah) [48]: Candidates for the detecting medium can be RPCs (resistive plate chambers) [39, 49], GEMs (gas electron multiplier) [50], or wire chambers, each read out with pads of approximate size ~ 1 cm^2 or small scintillator cells (~ 10 cm^2). Studies of the active media, cross-talk, gas mixtures, read-out systems, optimization of granularity, handling of additional pulseheight information are some of the many topics presently under investigation. As possible transducer options, Visible Light Photon Counters (VLPC) [51] and Silicon Photo-Multiplier (SiPM) [52] are being investigated.

3.2.3 Other Calorimeter-related Studies

a) *Low-angle Detectors*
The calorimetry at low angles includes instrumentation of the mask, covering down to about 30 mrad, and detection of beamstrahlung and pairs at very low angles, to about 5 mrad. These detectors are respectively called "low-angle tagger" (LAT) and "luminosity calorimeter" (LCAL) in the TESLA TDR [5]. The design must deal with calorimetric coverage, veto, lowest angle, crossing angle and fierce backgrounds. R&D has started [53]. Further work [54] is also being planned by Colorado [55], DESY, UCLondon, Minsk, IHEP Serpukhov and Tel Aviv, and the R&D will cover diamond

technology, crystal calorimetry with longitudinal segmentation, tungsten/gas-sampling and tungsten/Si-sampling.

b) *Photon Detectors*

Many calorimeter schemes use photon detectors for signal readout. The requirement of high-granularity motivates the development of multi-channel photon detectors. Present calorimeter designs require these devices to operate in a high magnetic-field. Therefore R&D on the following devices are on-going, aimed at high-sensitivity with magnetic-field-immunity: APD (avalanche photodiode) [1, 39, 56], HPD (hybrid photodiode), HAPD (hybrid avalanche photodiode), EBCCD (electron bombardment CCD) [1, 56], and SiPM (silicon photodiodes) [39, 52].

3.3   Muon Detector

Although the main purpose of the LC muon detectors [57] is to identify muons by their penetration through Fe, these detectors will also see significant deposits of hadronic energy since the calorimeters vary from 5.1 to 7.5 interaction lengths λ in depth. Thus, a properly instrumented muon system could also serve as backup calorimetry. Two candidate technologies, resistive plate chambers (RPCs) [58] or scintillation counter strips [59] are being studied, either of which may be used to instrument the gaps in the magnetic field iron flux return yoke for the central solenoidal field. The R&D efforts for both of these systems overlap sufficiently to discuss them in parallel. If alternate calorimetry designs, such as LAr, are postulated, with a larger number of λ's, then conventional muon tracking systems, such as wire chambers, should be considered. The most critical issues for the muon system are the development of low cost, reliable detectors, and the studies of muon background. The institutions involved in muon detector R&D studies are: INFN-Frascati, Kobe Univ and other Asian institutes, UC Davis, Northern Illinois University, Wayne State University and Fermilab.

- Muon System Mechanical Design.
  The engineering for the muon iron requires a detailed design that considers structural loads, construction techniques and installation of iron plates, detector planes, cables, etc. It is assumed that 4-5 cm gaps between the 10 cm thick Fe plates that make up the return yoke can be instrumented with RPCs, wire chambers or scintillation detectors.

- Monte Carlo and Tracking Studies.
  Studies are required to understand the effects of shower leakage on the energy-flow algorithms. Muon tracking software needs further development. Specific studies are needed for collisions at 0.8 to 1 TeV. The impact of background from hadron decays to muons, hadron punch-through, and from muons originating far upstream should be determined and understood in the forward and central muon detectors, and accounted for in the muon system design.

- Muon Hardware.
  Specifications for both RPC and scintillator based systems need further development in terms of dimensions, materials, construction plans and techniques,

readout hardware and front-end electronics. Prototype detectors must be built and tested. This, in turn, requires engineering to produce easily assembled, robust and reliable detectors and electronics. Cosmic ray testing (a test stand with data acquisition) will be required to provide feedback to muon system developers on questions of signal-to-noise, etc.

3.4   Particle ID

Particle ID derives from the measurements of many subsystems. The LC detector will surely make use of particle ID via dE/dx [60] if it is available, and if the main tracker is a gaseous TPC with many samples, as considered for TESLA, this will be valuable for physics. There remains the question as to whether a dedicated Cerenkov-based system should be considered, along the lines of the DELPHI RICH or the SLD CRID. It adds material in front of the calorimeter which will affect the ECAL performance and degrade the hermeticity, and the radial space requirement might be prohibitive, particularly in view of the greatly increased momentum range associated with the TeV-scale collisions. However, there remains some interest. For example, the SLD experience showed the synergy between a vertex detector having topological capability (separation between primary, secondary and tertiary vertices) and hadron ID. A charged kaon emerging from an established charm vertex is a clear signature for a charm or anti-charm parent quark. Such information may be extremely valuable in reducing combinatorial background in many multi-jet events with several leading heavy-flavour quarks. Such events are to be found in the SM (*e.g.* Higgs decay channels, $t\bar{t}$), or beyond SM processes (*e.g.* HA which can produce 12 jets if each of the SUSY Higgs particles decay to $t\bar{t}$). While it may not be possible to make space for a gaseous Cerenkov system, the DIRC technology pioneered by BaBar has been extremely successful, and may offer some potential for extending the range of K-π separation in the LC detector. At least, this possibility seems worthy of detailed study, in conjunction with the full exploitation of the unprecedented performance of the expected vertex detector. The Colorado State group in the US has been actively investigating this capability [61]. So far the studies have been limited to simulation and reconstruction software development within the JAS (Java Analysis Studio) framework.

3.5   Trigger and Data Acquisition

All LC detector designs include a "software trigger" as explained in the following [62]. Due to cross sections for the various physics processes differing by several orders of magnitude, highly efficient and flexible event selection and data acquisition (DAQ) are essential. The bunched operation modes of all LC designs have the common feature of a 3-order-of-magnitude longer time between bunch trains than the bunch-to-bunch separation. This suggests using the time between trains for the hardware-trigger-free and deadtime-free readout of all data generated during a whole train. Subsequent software event selection ("software trigger") using a type of filter farm will then analyse the full data to achieve the highest possible efficiency and flexibility.

All present LC detector designs are therefore based on a software trigger with the following assumptions [5]: dead time free pipeline during a bunch train, no hardware trigger, frontend pipeline with capacity for storing data from a complete train, and event selection by software.

The frontend of the subdetectors should be equipped with hit detection/zero suppression capability and readout channel multiplexing into a common readout line. Although the DAQ system for the LC detector is more relaxed than for LHC experiments, the frontend readout systems for the high granularity detectors impose demands sometimes beyond those for LHC, both for electronic integration and power consumption. This necessitates R&D for the frontend readout which must be covered by the specific subdetector groups. For the overall event building, proof of concept and the development of event selection strategies will require event-builder prototyping as well.

For the subdetectors the large number of readout channels demand development of high electronic integration and smallest possible power dissipation to reduce cooling needs, reduce dead space for the readout electronics and readout cables at the detector, achieve manageable data rates for the high granularity systems by online zero suppression, hit detection and data processing, and allow online monitoring and calibration of all frontend readout channels.

The central DAQ system itself will use commercial products available by the time it is built, and therefore no specific R&D for central DAQ hardware is warrented at this time. However for various test systems, a DAQ prototype should be provided which is based on today's commercial products. The only part of the central DAQ system needing hardware R&D is the common interface of the frontend readout systems to the central DAQ system. This common interface has to be specified and designed in close cooperation with the different detector R&D groups in order to ensure a unique interface or at least a small set of standardized interfaces for all subdetectors.

For the central DAQ mainly conceptual work is required to optimize the general design of the event building and the software event selection. A small scale central event-builder prototype using a farm of commercial computers and state-of-the-art network infrastructure could serve as a test setup to prove the concepts and develop event-filter strategies. Full event and background simulation will be essential to have as input to the prototype studies.

First tests and basic conceptual work are possible with available infrastructure as used in the FLC Farm at DESY . This infrastructure has only 100Mbit/sec network interfaces and thus cannot be used for testing event building via high speed network infrastructure, but it could serve as a prototype for test-beam applications.

The design and layout of a common frontend interface for the central DAQ could already be used in test beams. This should be done in parallel to the frontend designs of the different subdetectors prototypes in order to be ready for test beam operation and to reduce the efforts in the different R&D groups. Although first design ideas for the frontend readout have been discussed in some subdetector groups, common effort would be beneficial: this is missing up to now.

3.6   High Field Solenoid

All detector concepts under study assume a strong magnetic field of strength greater than 3T. The large volume required for this high-field magnet is a challenge, but experience is being gained by the 4T solenoid for CMS. This experience was utilized in [5] for the TESLA detector. The silicon-detector version in the American study [8] is considering a 5T solenoid which will also have a demanding design.

3.7   Machine-Detector Interface

Machine-detector interface and IP instrumentation are also important areas to study in order to achieve the anticipated physics goals. The followings topics are under investigation [63].

- Beam energy determination.
  At high energies an accuracy of 10^{-4} is needed, which should be achievable by improving the beam spectrometer designs used at SLC and LEP. At lower energies (GigaZ) an accuracy of 10^{-5} is required which has to be developed in a dedicated R&D program.

- Polarization measurement.
  Accurate measurement of polarisation to $\sim 10^{-3}$, required in particular for GigaZ running, has to be developed.

- Luminosity measurement.
  Issues related to understanding the luminosity delivered at the interaction point must be fully understood. In addition to the instantaneous and total integrated luminosity, many physics analyses also require a detailed understanding of the differential luminosity spectrum (dL/dE) resulting mainly from the large beam-beam interactions in the collision process. All foreseen measurements of particle masses, for example, are highly sensitive to the exact shape of this luminosity spectrum. Methods for optimizing the delivered luminosity will also be considered in this topic, due to the significant overlap in required instrumentation.

- Beam profile.
  A monitor of Bethe-Heitler pairs at very low angles would be useful as a real-time beam diagnostic and as an independent measurement of the luminosity. A collaboration of Hawaii, KEK, and Tohoku has carried out simulations and has begun R&D on a dedicated "pair monitor"[64], based on active pixel sensor devices at very low angles near the final beam quadrupoles.

- Quad stabilisation.
  This is a machine-detector-interface issue that is equally crucial for the detector. The bunch spacing will determine the hardware needed for quad stabilisation, which could affect significantly the design of the inner detectors.

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3.8   Detectors for the $\gamma\gamma$ Collider

The final states that a $\gamma\gamma$ experiment studies [5, 6, 65] are almost identical to those in an e^+e^- experiment, leading to similar detector requirements. The photon collider hardware imposes a few requirements on the detector. Also, the photon collisions themselves lead to some additional design constraints [66].

The laser pulses must be focused in the IR a few millimeters away from the IP. In the NLC design this leads to the inclusion of optics inside the beam pipe. Those optics add an additional 7cm of fused silica in the region from 35 - 100 milliradians. This will have an effect on low angle tracking, but should not generate additional backgrounds since it is outside the beam and e^+e^- pair-background stay-clear cones.

For TESLA a storage cavity for the laser pulse has been proposed by the Max Born Institute and DESY. Such a cavity probably makes a crossing angle between the laser and the electron beam necessary. In this design all mirrors, i.e. material, can be placed outside the detector. As a drawback, however, the dead region around the beampipe is somewhat increased.

In both designs the much higher particle flux at low angles requires a redesign of the low angle taggers if physics requires them also in the $\gamma\gamma$ case.

The Compton backscattering creates a large energy spread in the initial electron beam. This leads to a much larger disruption during the beam-beam interaction. The outgoing beam pipe aperture must be enlarged to accommodate this and a field-free drift region to the dump is required. This will preclude post-IP diagnostics on the beam and will increase the amount of neutron radiation from the dump reaching the vertex detector. For the NLC standard beam dump configuration the flux will be 10^{11} neutrons/cm^2/year at the IP. Standard CCD vertex detector designs will not be able to handle this. Either rad-hard vertex detectors must be used or the beam dump must be re-engineered to reduce the neutron flux. LHC vertex detectors are within the range needed for this application.

The photon collider has a higher event rate than the e^+e^- experiment due to re-solved photon events. The photon can fluctuate into a $q\bar{q}$ pair and thus has a hadronic component. It is expected that every event will have tracks in the barrel and end-cap region from underlying resolved photon events. These will have an impact on b-tagging, jet resolution, and event energy balance. LLNL has done preliminary work on characterizing the resolved photon backgrounds on the jet energy resolution [66]. The TESLA bunch structure, with 337ns between bunches, should allow the detector to resolve individual crossings. The NLC, with 2.8ns spacing, will not allow individual bunch crossings to be resolved and the consequences are much more severe than for e^+e^- collisions. The effect of these tracks on the detector performance needs to be well quantified before the time resolution requirements of the NLC detector can be specified.

In summary, the photon collider hardware modifications do not impose any detector constraints except for the vertex detector and the low angle taggers. Studies of the effect of resolved photon backgrounds on the reconstruction are needed before the detector requirements can be finalized.

4   Test Beams

Test beams are required to obtain much of the information in order to make technical decisions for the LC detector. Especially, new ideas and extensions to existing technologies will need to be tested with beam. For example, detector designs for high-resolution and high-speed CCDs, SiW electromagnetic calorimetry, a TPC, a silicon tracker, and other large volume tracking devices, will have to be tested with beam to make sure that designs can be reliably engineered into trouble-free detectors that can withstand beam conditions.

Test beam exposure will permit both software and calibration techniques to be developed and tested along with the hardware. Data acquisition, controls and monitoring, and algorithms for handling single particles such as e's, mu's, pions, kaons, and objects such as secondary vertices, charm and bottom particles, jets and missing energy must to be tested. Crucial concepts such as energy-flow algorithms, identification of neutral hadrons and measurement of their energies, as well as unprecedented efficiency and purity in separating b and c tagged events need to be verified. Achieving results in test beams will assure a full cycle of design, perhaps several cycles, and implementation with regard to issues such as installation, power, cabling, cooling, survey and alignment, magnetic field tolerance, reliability, efficiency, and the determination of operating parameters such as voltage current, cooling, and humidity, etc.

All of this implies, in some important cases, the development of sophisticated test beam facilities at reasonably high energies. Facilities already exist [67] at CERN, DESY, Fermilab, KEK and SLAC, but further development is warranted.

5   Conclusion

The material presented in this paper respresents the status at the time of LCWS02, August 2002 [12]. Much effort in linear collider detector R&D is already going on world-wide at universities and research laboratories. Many groups have already formed co-operations working on developments for specific detector components in an international context, and more of such co-operations are strongly encouraged. This should also facilitate the formation of experimental collaborations once the decision for a linear collider facility has been taken.

Given the challenging detector performances envisaged, it is necessary to strengthen the R&D efforts and to ensure coverage of all areas including simulation and reconstruction codes. This has been realized by the experimental community and interest in linear collider detector R&D is growing rapidly. In fact, many recent new proposals are not yet included here, since they are still in the preparatory stage. Therefore, this paper can only represent a first step towards informing the community. A web page [10] has been created with links to linear collider detector R&D projects. It will be kept up-to-date by the international contact persons. The information provided should ease the identification of uncovered or inadequately covered areas.

The physics programme of the linear collider is compelling and will be a formidable

challenge for the detector. The world-wide effort now being mounted to meet this challenge is reflected in this document.

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