Design Considerations for an International Linear Collider

The American Linear Collider Physics Group Executive Committee [1]

16 April 2003

Abstract

We describe the physics-motivated minimal design specifications for an e^+e^- linear collider. Machine options and upgrades are also discussed. We conclude that such a machine should have the following capabilities:

- Initial center-of-mass energy: $\sqrt{s}$=500 GeV
- Integrated luminosity at $\sqrt{s}$=500 GeV: 500 fb^{-1} within four years of physics running, corresponding to a design luminosity of approximately 2×10^{34} $cm^{-2}s^{-1}$
- Electron polarization: at least 80%
- Energy upgradeable to approximately 1 TeV or more
- Capability for occasional running at $\sqrt{s}$=91 GeV
- Accomodation for two experiment halls
- Possibility of a beam crossing angle

1 Purpose of this Document

At present there are large-scale international efforts [2] to design an e^+e^- linear collider (LC). Ongoing research and development programs are expected to produce one or more design proposals within a year. The purpose of this document is to use the conclusions drawn from numerous physics studies [3–5] undertaken over the past ten years to establish the parameters a linear collider should have in order to address the physics. The statements of fact cited in this paper are clearly outlined in those studies and have been widely reported. In addition to defining the parameters necessary for a minimal ("baseline") facility, this document also discusses several *options* for the use of the baseline facility (with little or no additional cost to the program), and several *upgrades* to the baseline which might be achieved at a later date with additional costs to the program. We do not prioritize these options and upgrades, as their relevance will depend on the physics discoveries from the initial running. Our values for the machine parameters are approximate; in some instances reduction of a parameter would still lead to a realization of the stated physics objectives with longer running.

2 Introduction

An e^+e^- LC is designed to elucidate the rich and complex physics that we expect to emerge at the electroweak energy scale. This scale, set by the Fermi coupling constant of the weak interactions, is roughly $G_F^{-1/2} \approx 300$ GeV. A comprehensive program of measurements – mapping out both the spectrum of particles and the precise details of their interactions – will enable us to understand some of the most urgent and compelling issues in particle physics today, including the origin of mass, the evolution of the very early universe, the nature of dark matter, and even the structure of space-time. We are fortunate that there are projects in the international high energy physics program that will begin to address these issues. The Fermilab Tevatron Collider, which collides protons with antiprotons, has the ability to probe this energy scale and may yield exciting discoveries in the next few years. Around 2007, the Large Hadron Collider (LHC) at CERN will begin to operate, and the energy of its proton-proton interactions will be sufficiently high that major discoveries are expected.

In spite of these powerful new research tools, however, there is strong consensus in the U.S. high energy physics community [6] that a high-energy e^+e^- LC will be essential for addressing the fundamental issues of the electroweak scale. The dramatic progress in testing and understanding the Standard Model over the past three decades has demonstrated the power of a two prong approach, using the strengths of both e^+e^- and hadron colliders. There is consensus that the same two prong approach is required now to understand the electroweak scale, because the physics is likely to be as rich and complex as that at the energies studied in the past. The impact of a linear collider will be particularly strong if significant LC physics output becomes available before the end of LHC running. Similar conclusions have been reached by physicists in Europe and Asia, and several major laboratories have strong efforts towards developing and building an e^+e^- LC with the required capabilities.

The first target of experiments at the electroweak scale will be the Higgs sector. The Standard Model (SM) predicts that there is a field responsible for generating particle masses, with an associated new particle (the Higgs boson) which we have not yet seen. The Tevatron Run-II or the LHC will definitely find this particle if its properties are as predicted by the SM. The precision electroweak measurements indicate that its mass is less than 200 GeV at 95% CL, and it is predicted to have a rich pattern of decay modes. While a hadron machine is expected to discover the Higgs boson and measure some of its properties, the LC will be necessary to determine all the branching fractions and couplings to different particle species with the precision required to establish that the Higgs mechanism is responsible for the masses of all the SM particles. Even if the Higgs-like corrections indicated by precision electroweak measurements turn out to arise from a different particle, any particle theoretically viable as a Higgs boson should have a mass below approximately 800 GeV.

Despite its success, the SM suffers from a severe fine-tuning problem, since the Higgs mass is not stable against radiative corrections. We therefore expect new physics and additional particles at the energy scale near 1 TeV. Several attractive theoretical ideas have been proposed which link the SM to the super-TeV scale, e.g., supersymmetry (SUSY), dynamical electroweak symmetry breaking such as technicolor and topcolor, large extra dimensions and TeV-scale quantum gravity, TeV-scale extra dimensions, little Higgs, Higgs as gauge bosons, etc. In all examples we are aware of, there are either new quanta or effects observable at the LHC and LC, with each machine providing crucial information.

Some candidates for the physics that explains the electroweak symmetry breaking provide new stable weakly-interacting particles that may be the dark matter inferred from astrophysical observations. If their masses are within the reach of the collider, we will be able to produce the dark matter particles in quantity and study their couplings. Once the couplings are determined precisely, we will be able to calculate how much cosmological abundance the particles should have and compare the accelerator-measured parameters to the cosmological observations. If they agree, we will know what the dark matter is and understand the evolution of universe from when it was only 10^{-8} sec old [7].

3 Machine Energy Range and Luminosity

3.1 Initial Energy and Luminosity

The initial linear collider should be capable of delivering 500 fb^{-1} *in the first 4 years* *of operation (after commissioning) at a maximum $\sqrt{s}$=500 GeV.*

The initial LC physics program will be the detailed study of properties of the Higgs boson sector and probably also new particles predicted by non-SM theories. With the strong indication from current precision electroweak results that the Higgs boson exists with at least one particle having a mass lower than 200 GeV [8], and since the SM Higgs production rates are lower than those for most popular new-physics models, *the initial machine energy and luminosity should be designed for 200 GeV Higgs boson measurements.* The Higgstrahlung production mechanism $e^+e^- \rightarrow Z^* \rightarrow ZH$ will play a central role in the studies, thus the kinematics for this process sets the required machine characteristics [3][Ch. 2, 8.2.2]. The peak position in the Higgstrahlung cross section varies approximately as $\sqrt{s_{peak}} \approx 1.4 m_H + m_Z - 30$ GeV, corresponding to 220 – 340 GeV for Higgs masses in the 115 – 200 GeV range suggested by current measurements; the Higgs production rate falls off as $1/s$ above the peak production energy. The energy range suggested by these calculations is similar to that needed for pair production of the top quark, another important object for study by the LC. One concludes that the initial energy reach of the LC should be above 400 GeV, allowing for the Z mass and some extra energy to enhance the kinematic factors [3][Ch. 1]. However, to truly verify a Higgs boson, it is essential to measure its self-coupling, and this requires running at 500 GeV (for a 200 GeV mass Higgs boson). This coupling can be measured at 500 GeV with a precision of 20% using $e^+e^- \rightarrow hhZ$ [3][Ch. 3, 8.2.4], [10].

In addition to measuring the Higgs boson properties to high precision, the physics program of the LC should include searches for new particles and precise measurement of some of their properties in the range of energies indicated to be of interest by the current measurements. If SUSY exists and accounts for some of our observations, then an important mission of the LC will be to identify particle spectra and couplings. Scenarios for SUSY spectra have been reported in several references [3][Ch. 4], [9]. Study of the SUSY spectra benefit from the highest possible initial energy and continued running at TeV energies, as described later. The integrated luminosity necessary for measuring SUSY properties while LHC is still running are commensurate with the Higgs-driven design luminosity. Scenarios for other possible new physics have been considered and are described in, e.g., reference [3][Ch. 2]. These arguments further support 500 GeV for the preferred initial machine energy.

The LC should measure the Higgs couplings to a precision of approximately 5% in order to distinguish the SM Higgs from those arising in extended models [3][Ch. 3, 8.2.5], [10]. The SM peak Higgs cross sections vary from about 300 fb at $m_H = 115$ GeV to about 70 fb at $m_H = 200$ GeV. Assuming that the luminosity scales linearly with $\sqrt{s}$, the higher end of the mass range dictates the LC luminosity requirements, which have been studied in detail (Chapter 3 of reference [3]). These measurements require an integrated luminosity of 500 fb^{-1} at $\sqrt{s}$= 500 GeV.

Running at machine energies lower than the maximum value should be considered in a run plan. For analyzing the Higgs boson spin structure, reasonable running near

ZH threshold may be necessary [3][Ch. 3, 8.7]. For a Higgs boson of mass 120 GeV, this can be accomplished with approximately 60 fb^{-1} of data around the threshold region, which could be achieved in a reasonable fraction of a year if luminosity scales like $\sqrt{s}$. Depending on the physics results obtained at maximum energy, longer running could be warranted at the Z pole or at W^+W^- threshold; such run options are considered later in this document. Another important particle to study at the LC is the top quark. The top quark pair threshold region (350 GeV) is an interesting laboratory of perturbative QCD. If the top quark plays an important dynamical role in the electroweak symmetry breaking, its couplings and form factors may show deviations from the Standard Model. Measurements of, e.g., the top mass to 40 MeV precision or its width to 2% would require approximately 100 fb^{-1} [3][Ch. 6, 2.5].

The physics emerging from the first years of LC operation will dictate how much time should be devoted to running at 500 GeV (or lower) and when the physics program should be interrupted to upgrade the machine to higher energy. It is easy to imagine a rich decade of physics at 500 GeV, devoted to exploring electroweak symmetry breaking and some emerging new physics such as SUSY, or even a return to precision electroweak measurements at the Z pole or W^+W^- threshold. For establishing minimal machine requirements – the purpose of this document – we focus on essential study of the Higgs boson at 500 GeV. If the Higgs properties are to be measured over a four year period, the preceeding arguments dictate the following minimal machine parameters:

- An initial upper energy reach of $\sqrt{s}$=500 GeV.
- An integrated luminosity of 500 fb^{-1} in four years after commissioning, corresponding to a design luminosity of approximately $2\times10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$ at $\sqrt{s}$=500 GeV.
- A beamstrahlung-induced energy spread comparable to initial state radiation so as not to substantially degrade the energy spectrum of the e^+e^- collisions.
- Ability to run at $\sqrt{s}$=90–500 GeV at luminosities commensurate with $\sqrt{s}$-scaling of the luminosity at 500 GeV.

3.2 Upgrade Energy and Luminosity

The accelerator should be upgradeable to approximately 1 TeV and possibly higher.

As addressed in the Introduction, precision electroweak measurements and astrophysical arguments strongly indicate new physics in the energy range of 100 GeV to beyond 1 TeV. Exploration of this region will be crucial for our understanding of the Standard Model and for addressing the indirect evidence of new physics. The LC must be a major facility advancing high energy physics through the next decade and significantly beyond – it must eventually be capable of exploring the energy scale we know to be of interest. Regardless of the machine technology, the site should not preclude upgrade to the TeV region.

The best place to study rare or low-rate Higgs decays is at higher energy using W^+W^- fusion, $e^+e^- \to h\nu\bar{\nu}$. This process has a cross section which increases with energy [3][Ch. 3, 3.2]. Running at 800-1000 GeV will allow for good determination of small branching fractions such as $h \to \mu^+\mu^-$ with a fraction of the integrated luminosity it would take using the ZH process at 500 GeV. For light Higgs bosons, an important channel to measure is radiation of a Higgs boson by a top quark in $e^+e^- \to t\bar{t}h$ [3][Ch. 3, 8.2.2].

Supersymmetry is an attractive candidate for answering many of our current theoretical questions, with all SUSY models predicting spectra that have some particle masses above 500 GeV [3][Ch. 4, 2.1]. Since we don't know the mass scale of SUSY nor the SUSY breaking pattern, we can say generally that we want the highest possible center-of-mass energy in order to maximize the probability that the LC will be in a position to study many SUSY particles .

Other new physics processes benefit from the highest energy reach, even at reduced luminosity. For example, limits obtained from the reaction $e^+e^- \to f\bar{f}$ on fermion compositeness and extra gauge bosons scale as $(s^2L)^{0.25}$ [3][Ch. 5]; for graviton exchange, the limits scale as $(s^3L)^{0.125}$ [3][Ch. 5]. One can invent models, such as topcolor, that contain new physics that masks the effects of a large Higgs mass in electroweak fits. In strong symmetry breaking scenarios one will want to study the processes W^+W^- to W^+W^- ZZ, $t\bar{t}$ [3][Ch. 2, section 3].

Table 1 summarizes the physics potential as a function of machine energy and luminosity.

$\sqrt{s}$ (GeV)	LC Integrated Luminosity $\sim$500 fb^{-1}	$\sim$1000-2000 fb^{-1}
350-400	low-mass h: production rates, BRs, spin; $t\bar{t}$ production; low-mass SUSY	
500	WW fusion, hWW; more SUSY states; $h \to t\bar{t}$ for high-mass h	rare h BRs ($h \to \gamma\gamma$,$h \to \mu^+\mu^-$); low mass h self coupling
800-1000	possibly H, A, H^+ mass; higher mass SUSY; new theories; extra dimensions	rare h decays via WWh; $t\bar{t}h$, hhZ;
1000-1500	likely H, A, H^+ mass; SUSY model parameters ?; strongly interacting WW ?	H, A, H^+ BRs; heavier Higgs self-couplings; strongly interacting WW?

Table 1: Physics potential that opens as LC energy is increased, for moderate and high integrated luminosities. Notation: h refers to the lowest mass Higgs boson; H, A, H^+ refer to higher mass Higgs bosons in extended models.

4 Beam Polarization

The machine should be capable of 80% electron polarization or better. Positron polarization is highly desirable as an upgrade.

Parity violation is an essential feature of the weak interactions, and thus the e^+e^- cross sections and angular distributions depend on the beam polarization states, and these differences are crucial for identifying the quantum numbers of new particles. Transverse beam polarization allows for measurement of relative phases of scattering amplitudes. Polarization can be chosen to enhance signals over background. In particular, the choice of right-handed electrons suppresses W boson pair production, which is often the dominant background to new particle analyses. Initial-state polarization can lead to polarization of produced particles and increased sensitivity to their decay patterns. Polarization can also give sensitivity to new couplings forbidden in the standard electroweak model.

4.1 Electron Polarization

The importance of electron beam polarization has been demonstrated in Z production at SLC, where about 80% electron polarization was achieved. This level of electron polarization provided an effective luminosity increase of approximately a factor of 25 for many Z-pole asymmetry observables. At a linear collider, electron polarization will increase sensitivity to form-factor studies of W^+W^- and $t\bar{t}$ states, control the level of W^+W^- backgrounds in new physics searches, provide direct coupling to specific SUSY chiral states, and enhance sensitivity to new physics that would show up in the spin-zero channel. For example, with 100% (80%) electron polarization, W^+W^- production can be fully (80%) eliminated for right-handed polarization or be enhanced by a factor of 2 (1.8) over the unpolarized case for left-handed polarization [3][Ch. 12, 2.1]. Electron polarization of 80% or more is very effective in identifying selectrons in SUSY theories [3][Ch. 4,3.1]. Beam polarization extends the search range for new physics, where parity violation is a signature in virtually all models, and therefore e^- polarization is essential to the LC program.

4.2 Positron Polarization

The baseline designs for NLC/JLC and TESLA include a polarized electron beam, but currently no provision for polarized positrons because a feasible design has not yet been realized. Positron polarization greatly enhances the LC physics. First, it increases the effective polarization, where effective polarization is defined as $\frac{|P_-|+|P_+|}{1+|P_-P_+|}$; this results in higher production rates of a number of physics processes, including ZHH and WWHH. Annihilation through a photon or Z^* takes place from the polarization states $e^-_L e^+_R$ and $e^-_R e^+_L$ only. By polarizing the positron beam opposite to the electron beam, these channels are enhanced and better defined. For 80% electron polarization, the introduction of 60% positron polarization leads to an effective polarization of 95% and an increase in the annihilation rate by a factor 1.5 [3][Ch. 12, 2.2]. Additionally, positron polarization aids in background suppression. With an e^-_R beam, introduction of a 60% polarized positron beam leads to a further factor of three background suppression of W pairs. Positron polarization can also be used to control signal and background reactions involving t-channel exchange. If the selectron appears at the LC, positron polarization can select whether the partner of the e^+_L or e^+_R is produced. Single W^+ production is a background for some analyses, and this is controlled by using a polarized e^+_L beam; electron polarization has only a small effect. *Positron polarization schemes are under study, and development of such schemes should continue because of the significant advantages positron polarization contributes to the physics program.*

5 Interaction Region Configuration

5.1 Beam Collision Considerations

It may well be desired to incorporate a crossing angle for the colliding beams.

X-band time structure requires a crossing angle at the interaction region (IR) to avoid parasitic collisions; NLC has chosen 20 millirad and JLC 8 millirad. Superconducting technology (TESLA) may not require a crossing angle, but neither does the machine design require head-on beams. However, physics considerations may require post-collision beam diagnostics which could only be realized if the beams collide at a small crossing angle. The ALCPG working group on Beam Instrumentation is currently studying this issue to quantify the diagnostics instrumentation required for precise measurements of energy, energy spread, and polarization. Furthermore, beam dumping and background minimization can be better optimized with an IR crossing angle. Therefore, the site plan should not preclude the possibility of a beam crossing angle.

With a crossing angle, separate beamlines can be used to cleanly bring the disrupted beams to the dumps. This facilitates beam optics in the extraction line that allows precise measurements of the beam energy, energy spread and polarization. Additionally, instrumentation for measuring the characteristics of the disrupted beam and beamstrahlung may improve the determination of the luminosity-weighted beam energy and polarization. The beam energy spread ($\sim$1000 ppm rms for TESLA) and luminosity-weighted beamstrahlung energy loss ($\sim$25000 ppm) are large compared to the 50-200 ppm desired precision for measuring the top mass, Higgs mass, W mass and A_{LR}. The luminosity-weighted depolarization may be as large as 0.5% at a 500 GeV LC, larger than the targeted 0.1-0.25% precision needed for precision measurements of

SM asymmetries. Extraction line polarization measurements may be needed to achieve the desired precision.

5.2 Number of Collision Halls

The facility site plan should support two interaction regions.

Two collision halls will be essential if the highly desirable $\gamma\gamma$ or $e^-\gamma$ upgrades are realized. But there are also strong arguments in support of a second detector hall regardless of the $\gamma\gamma$ upgrade. A second detector will allow for a different approach in making important measurements, and would also allow for the staging of newer detectors optimized for specific physics or implementing technologies superior to the initial detectors. Historically, we have found that multiple dectectors yield better physics results than a single detector by virtue of the ability to cross-check important physics discoveries and measurements, and – perhaps most importantly – by virtue of the competition between the collaborations, which hastens the pace of discovery. The efficiency of operation would be higher too, since the maintenance of one detector could be planned while the other is accumulating data.

A single detector would not fully exploit the physics capabilities of such a major facility. The LC will be a research facility for decades of exploration. We will be providing the opportunities for more than a generation of physicists and the training opportunities for young scientists and engineers. A second IR supporting specialized detectors and experiments would enhance these opportunities at a small (~3-5%) fraction of the overall cost and provide good insurance for measuring the physics.

6 Running at the Z Pole and W^+W^- Threshold

The machine should be capable of some periodic running at the Z resonance. High statistics running at the Z or at W^+W^- threshold is desirable as an option.

Precision physics is a central part of the LC mission, and this will require good calibration of the detectors. This will require occasional running at the Z resonance after major detector changes or extended down periods. Typical cross sections of calibration processes are four orders of magnitude larger at the Z resonance than at 500 GeV. Detector calibrations are expected to require approximately 2 fb^{-1}; this could be accomplished in a few days of running on the Z; *the machine should be capable of such an energy change and return to high energy in a time scale of one month or less.* At this point in time, the detector working groups need to understand better the frequency of running at the Z pole that will be required.

Running at the Z resonance (so-called "Giga-Z" program) and at W^+W^- threshold could significantly refine the current understanding of electroweak parameters, even with only $1/\sqrt{s}$ extrapolation of the baseline luminosity [12]; this would correspond to approximately 4×10^{33} cm^{-2}s^{-1} at $\sqrt{s}$=91 GeV. This physics program would be worthwhile with approximately 10^8 Z; at this level of statistics, the current uncertainty on the weak mixing angle could be reduced by a factor of 5. If positron polarization is possible, the measurements would be even better. Such Z or W^+W^- running would not constitute the initial energy-frontier mission of the LC, but it should be considered as an option, depending on the physics realized at the initial maximum energy.

7 Collision Options

The baseline machine should have the option of e^-e^- *collisions. The machine should be upgradeable for* $\gamma\gamma$ *and* $e^-\gamma$ *collisions.*

The baseline facility should include the capability of e^-e^- collisions at a luminosity within an order of magnitude of the e^+e^- design. The e^-e^- capability could be considered in the run plan both for measurements of e^-e^- interactions and as a low-background method for generating $\gamma\gamma$ and $e^-\gamma$ collisions. There are specific scenarios in which experiments with e^-e^- collisions make a major contribution to the LC physics program. The most important of these occurs if the selectron is seen at the LC. In this case, selectron pairs can be produced in e^-e^- collisions by t-channel exchange of neutralinos. This process offers the best setting for high-precision measurements of the selectron masses and the neutralino masses and mixing angles. Møller scattering is the LC reaction most sensitive to contact interactions and electron compositeness [3][Ch. 14, 2.1].

With an upgrade for laser-backscattered photon beams, the e^-e^- option can be utilized for a 'Higgs-factory' based on high energy photon beams that are optimized for s-channel production of a Standard Model-like Higgs boson in the mass range between 100-130 GeV [3][Ch. 14, 2.2]. Such a factory would permit high precision measurement of the $h \to \gamma\gamma$ partial width, which is sensitive to new charged particles such as the top squark, and also the top Yukawa coupling. In principle, a $\gamma\gamma$ collider can be constructed as a machine upgrade by laser backscattering from incident e^+e^- or e^-e^- beams, but choice of e^-e^- results in lower backgrounds. In all scenarios a $\gamma\gamma$ collider will require a second interaction region, with a beam crossing angle and the optics and laser system needed to produce the photon beams from Compton backscattering. A high energy $\gamma\gamma$ collider in one collision hall would offer unique measurements due to the fact that (1) the effective cross sections for producing Higgs and Supersymmetric particles are as large or even larger than the corresponding ones for e^+e^-, and, (2) the capability of this machine to produce linearly polarized beams not only can provide conclusive information about the charge-parity (CP) nature of these particles, but also will allow us to detect any CP admixture [3][Ch. 13, section 2]. In addition, certain rare decays that are highly sensitive to parameters of the Minimal Supersymmetric

Standard Model (MSSM), such as $h \to \gamma\gamma$, $h \to \gamma Z^*$, and $h \to ZZ^*$ can be very well measured due to the low background level. A $\gamma\gamma$ collider could measure the spectrum and CP properties of the heavier Higgs bosons in extended models in $\tan\beta$ and M_A regions that are not accessible to the e^+e^- machine or the LHC.

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