The International Linear Collider – Physics, Collider and Experimentation

The discussion in this document is largely based on the 2013 ILC Technical Design Report (TDR). Volumes 1, 2 and 3 of the TDR respectively cover the physics motivation, the accelerator systems design and related R&D, and detector designs and related R&D.

1. Physics goals of the ILC

Among the great mysteries of elementary particle physics, there are three that are likely to be solved by new information from experiments at the TeV energy scale. These concern the three areas in which the Standard Model of particle physics is incomplete as the theory of nature: First, though the Standard Model incorporates a simple phenomenological model of spontaneous symmetry breaking through its Higgs field, the Standard Model gives no understanding of this symmetry breaking. It does not provide a mechanism for the phenomenon or even predict the mass scale at which it occurs. Second, the Standard Model does not provide a particle to describe the "dark matter" that makes up 80% of the mass in the universe. Third, the Standard Model does not provide a mechanism to generate the baryon-antibaryon asymmetry of the universe.

The discovery by the ATLAS and CMS experiments of the "Higgs-like particle" near 125 GeV – and the exclusion of the possibility that the Higgs boson could be at higher mass – gives us a direct path by which experiments can clarify the origin of the symmetry breaking of the electroweak interactions. It has long been appreciated that an electron-positron collider operating in the center of mass energy range of 250 GeV to 1 TeV would be an ideal instrument for the precision study of the Higgs boson. The discovery of the new particle now allows us to map out a specific program of experiments. This program accesses all of the Higgs boson production reactions shown in Fig. 1.

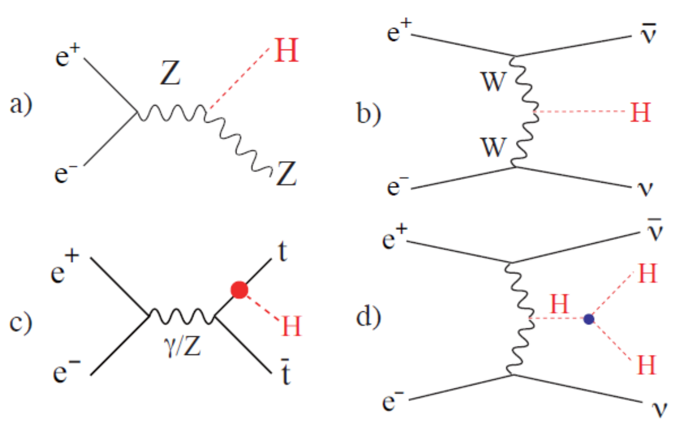

Figure 1: Feynman diagrams for Higgs boson production mechanisms at the ILC.

The Higgs boson program of the ILC begins at the energy of 250 GeV, near the peak of the cross section for $e^+e^- \to Z\,h$. The presence of a Z boson at the energy appropriate to recoil tags the Higgs boson events. This allows direct measurement of the Higgs boson branching ratios. The ILC detectors can identify and separate the various predicted Higgs decays, including the two-jet hadronic decays to b and c quark pairs, and gg. The Z tag also allows the ILC experiments to measure the branching ratio to invisible modes, and also to unexpected models with exotic long-lived particles. Measurement of the peak in the *Z* recoil energy also gives a precise determination of the Higgs boson mass.

At higher energy, the *WW* fusion process of Higgs production, $e^+e^- \rightarrow \nu\nu h$, turns on. Measurement of this process at the full ILC energy of 500 GeV gives a model-independent precision measurement of the Higgs boson total width. Experiments at 500 GeV also give first measurements of the Higgs boson coupling to top quark pairs and of the Higgs boson self-coupling. At a center of mass energy of 1000 GeV, all of the Higgs boson production reactions are fully accessible and the Higgs boson branching ratios can be studied with even higher precision. A complete review of the Higgs boson program of the ILC, with numerical estimates of the experimental capabilities and comparison to the expectations for the LHC, can be found in Vol. 1 of the TDR.

Models that repair the incompleteness of the Standard Model and give dynamical explanations for electroweak symmetry breaking necessarily contain additional particles beyond the Higgs boson. These might be the particles of an extended Higgs boson sector, or exotic partners of the quarks, leptons, and gauge bosons. For many of these particles, there are strong arguments that their masses lie in the ILC energy range. New particles beyond the Standard Model have not yet been discovered at the LHC, but there is still great opportunity to discover such particles when the LHC operates at 14 TeV. The LHC discovery of new strongly interacting particles with TeV masses could well point to additional new particles with only electroweak interactions that lie in the ILC energy range.

The TDR discussion reviews the current picture of models of new physics, incorporating what we have learned from the LHC measurements at 7 and 8 TeV, and surveys the opportunities that these models offer for the ILC experiments. For any new particle in the ILC energy range, the ILC provides a rich program to clarify its properties. The ILC experiments will be able to measure the masses with high precision, determine the electroweak quantum numbers and measure any associated mixing angles, and measure the decay branching ratios in a model-independent way.

In models in which the Higgs boson is composite or a part of a complex new sector, the interactions that lead to the light Higgs boson must also leave their imprint on the Standard Model particles, especially on the top quark and the *W* and *Z* bosons that couple to it most strongly. The ILC experiments offer powerful capabilities to measure the electroweak couplings of the quarks, leptons, and gauge bosons. The estimates of the precision expected for probes of electroweak couplings and discussions of the importance of these measurements to the more general question of the origin of electroweak symmetry breaking are given in the TDR. They will supersede the precision of the existing data and enable to study new physics at energy scales beyond the center-of-mass energy of the ILC.

Many models of dark matter give as its origin a new stable particle with its mass in the hundred-GeV range. For such models, it would be ideal to collect experimental measurements of the properties of the particle and use these to predict the cosmic density, for comparison to astrophysical observations. Several examples of models of new physics in which the ILC measurements are sufficiently detailed to make this comparison possible are also discussed in the TDR. Models of baryogenesis based on new physics at the TeV scale require new parameters of CP violation in a Higgs boson sector that is necessarily extended beyond that of the Standard Model. Experimental tests of these models require detailed probes of these new Higgs particles.

The discussion above of the ILC program on the Higgs boson emphasized the ability of the ILC to run at any energy within its range that might give the greatest physics potential. This is a unique advantage of a linear collider. The accelerator can run with only minor modifications at any energy below its design energy, with instantaneous luminosity roughly proportional to the energy. If higher energy is needed, the main linacs can be extended naturally. There are limits, of course, but the ILC is designed to run effectively over a very broad range in energy. Table 1 summarizes the most important reactions that will be studied by ILC experiments at a range of possible energy settings.

Energy	Reaction	Physics Goal	Pol.
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	A
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	H
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	H
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	A
	$e^+e^- \to WW$	precision W couplings	H
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	L
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	A
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	H
	$e^+e^- \to Zhh$	Higgs self-coupling	H
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry	B
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states	B
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	L
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	L
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	L
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	B

Table 1: Major physics processes to be studied by the ILC at various energies. The table indicates the various Standard Model reactions that will be accessed at increasing collider energies, and the major physics goals of the study of these reactions. A reaction listed at a given energy will of course be studied at all higher energies. Beam polarization is always important for the ILC physics, but the specific use of beam polarization depends on the process under study. The last column encodes these uses, as explained in the TDR Volume 3.

An important feature of the ILC is its ability to collide polarized e^- and e^+ beams, with left- or right-handed polarizations of ±80% and ±30% respectively. At energies above the Z the left- and right-handed spinning electrons are different elementary particles with distinct electroweak quantum numbers. In particular, the left- and right-handed electrons couple differently to the SU(2) and U(1) components of the Standard Model gauge group, so the different polarized reactions access different slices of the electroweak interaction. Particular signal or background reactions can be enhanced or suppressed by choosing the appropriate polarization states. For example, SM e^+e^- processes can be enhanced by choosing the initial state to be ($e_L^- e_R^+$) giving a factor of up to 2.3 increase in effective luminosity. Polarization asymmetries are themselves valuable probes of the new physics, and the possibility of positron polarization increases the effective polarization from 80% to near 90%, substantially improving the precision of such measurements.

The flexibility of the ILC in the choice of energy and polarization is exploited in the physics analyses described in the TDR. It is an important advantage of the ILC design that the precise energy and polarization settings can be chosen year by year in response to ILC discoveries and complementary information from the LHC program. The ILC thus offers a rich experimental program that addresses the most important open issues in elementary particle physics.

2. The ILC Accelerators and the GDE Program

The Global Design Effort was started in 2005 after superconducting RF was selected as the technology on which to base the accelerating cavities for the ILC. An aggressive goal of 35MV/m was adopted for the cavity gradient with a cavity yield at or above 90%. At the time this represented a ~50% increase on the existing results from a 1.3 GHz structure. A multi-year global R&D program was created aimed at achieving this goal. Initially only cavities fabricated at a single European vendor had achieved such a performance, and with a low probability. There were no industrial manufacturers in either the US or Asia capable of meeting these demanding specifications. A significant fraction of the GDE resources were devoted to the technology program, and by the end of the program cavities meeting the performance specifications were in production in all three regions. Attention is moving to the fabrication of the cryomodules, each of which contains eight or nine meter-long 9-cell cavities. The two linacs will contain 1800 cryomodules. The XFEL Project in Germany will provide significant experience in the near future as the production cycle of very similar cavities and cryomodules starts.

The main technical risks for achieving the luminosity and energy specifications were identified early in the program. These were (1) emittence dilution in the positron damping ring arising from electron cloud effects, (2) beam control to achieve a small spot size at the interaction point, (3) fast bunch injection into and extraction from the damping rings, and (4) the operation of cryomodules close to their maximum gradient with high beam currents. Each of these topics became the focus of specific beam test programs at the CESR ring at Cornell (1), the ATF facility at KEK (2,3), and the FLASH FEL facility at DESY (4). The success of those programs has brought new capabilities for general application in accelerator physics. In addition to these beam-based programs, cryomodule technology has been developed through testing at KEK, Fermilab, and DESY.

The GDE TDR describes a detailed design for the 500 GeV ILC, although the engineering work for industrial production and adaptation to a specific site remain. There are no outstanding issues requiring R&D that would prevent this design from being realized. The TDR machine simplified and optimized earlier designs on the basis of the

R&D results so as to minimize costs while addressing items such as operation at energies both higher and lower than the nominal baseline. The addition of positron polarization was explored. The critical elements for 1 TeV operation (the beam delivery region and beam dumps) are incorporated into the design so that adiabatic increases in energy could be achieved. This design then provides the basis for a value cost estimate, labor estimate, and operating power requirements. A zeroth order schedule was developed with civil construction and cryomodule production the determining items in a nine-year construction cycle. Figure 2 shows the layout of the ILC described in the TDR and Fig. 3 shows the schedule for construction and commissioning in a mountainous site.

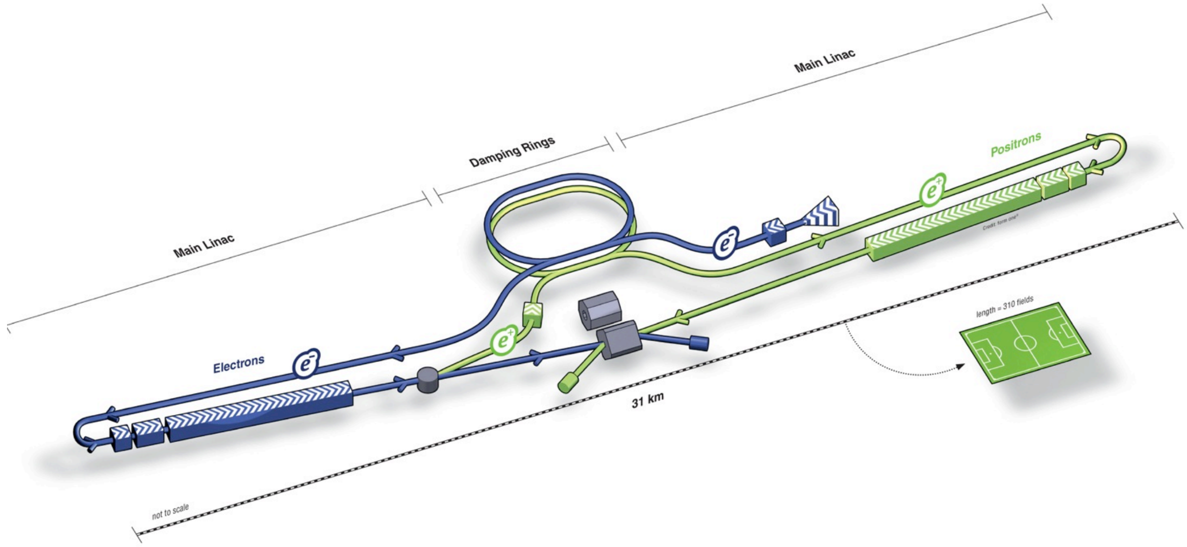

Figure 2: Layout of the ILC accelerator systems.

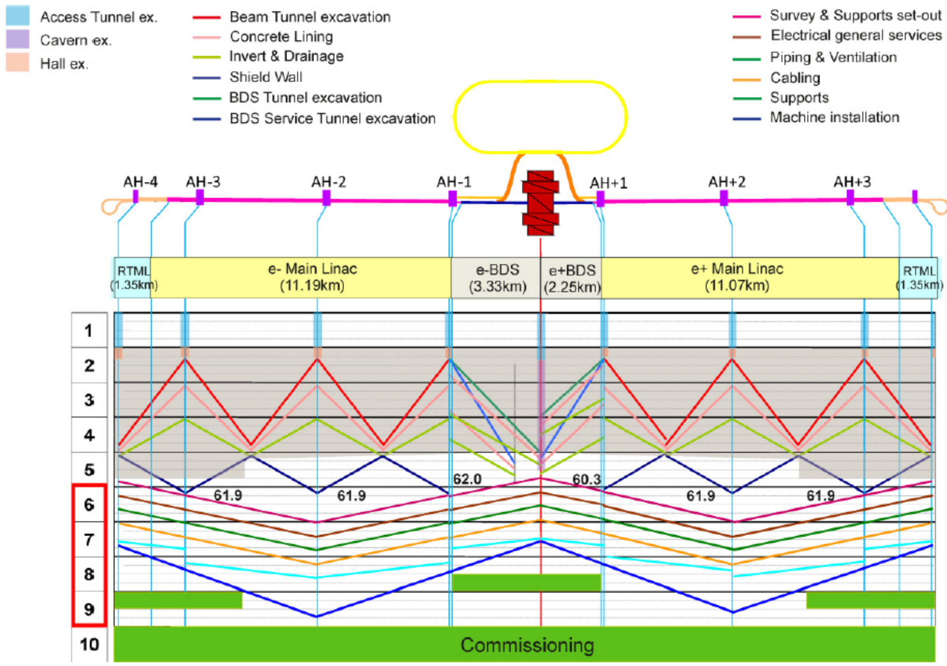

Fig. 3 ILC Construction, installation and commissioning schedule.

Currently the Japanese HEP community has launched a strong push aimed at establishing the viability of siting the ILC in Japan. This has involved the HEP community, politicians at the local and national level, and industrial collaboration. They aim to come to a national decision by the end of 2013. This proposal has received strong support from the European HEP community and will be presented to the US as part of the upcoming Snowmass-style meeting. Motivated by the recent LHC discovery of a Higgs like particle, the Japanese proposal involves a phased implementation of a 500 GeV machine.

3. Experimentation at the ILC

Achieving the physics goals for the ILC requires experimental detectors of unprecedented precision in tracking and calorimetry. However, unlike at the LHC, the interesting processes have cross sections that are much larger in proportion to the backgrounds and the environmental conditions are much more benign. (At the ILC, the Higgs production cross section is about 1% of the total cross section whereas at the LHC the fraction is about 10^{-9}.)

The ILC Research Director has overseen a global program of R&D to demonstrate that the precision goals can be achieved. Several proposals for detector concepts were submitted, and in 2009 the ILD and SiD concepts were validated. Subsequently these two proto-collaborations developed the detailed designs presented in Vol. 3 of the 2013 TDR, and conducted a series of benchmark physics studies that demonstrated that the physics goals could be met, both for operation at 500 GeV or below, and at 1 TeV. The two detectors would be moved on and off the beam line at regular intervals to allow cross-checking of new results, stimulate competitive new techniques, and to provide backup in the case that one of the detectors requires repairs.

The ILC detectors will improve on the LEP, SLC, Tevatron and LHC detectors in the precision of their tracking and calorimetry. The ILC beams provide an environment so benign that it is possible to design detectors with minimal material in the tracking volume. The angular coverage of the tracking will be enhanced over LEP. The calorimetry will make use of the particle flow algorithm (PFA) to reduce the uncertainty in calorimetric dijet mass measurements by a factor of two over what has been achieved at previous colliders. These improvements are driven by physics requirements, to obtain the Higgs boson mass at the highest precision, and to discriminate the W and Z bosons in the hadronic decays. They will also bring improvements to event reconstruction in many other aspects of QCD and electroweak measurements.

The overall design of both ILD and SiD is guided by the choice of PFA for obtaining unprecedented energy resolution for jets. In this approach, charged particle energies are taken from the tracking detectors and their energy deposits in the calorimeter are removed from consideration, leaving the calorimeter to provide the measurements of photons and neutral hadrons. A key requirement is that the calorimeter deposits can be cleanly associated with individual incoming particles, thus placing high demands on transverse shower spreading and calorimeter segmentation. The PFA approach dictates that the solenoidal magnets be placed outside the calorimetry (the field strength is 3.5 Tesla for ILD and 5 Tesla for SiD). Extensive tests in beamlines and in simulation have demonstrated that jet energy resolutions between 3 and 4% can be achieved over the full energy range of the ILC.

The track momentum resolution goals also extend those of the LHC experiment, and are set, for example, by the requirements for precision mass measurement of a Higgs boson recoiling from a Z boson. The ILD approach is based on a time projection chamber, augmented by silicon microstrip detectors, whereas SiD specifies a more compact tracker based solely on silicon. Both experiments include precision silicon pixel detectors close to the beam line, permitted in the lower radiation environment of e^+e^- colliders, so as to efficiently identify the b, c and τ decay products of Higgs bosons.

Representations of the two detectors are shown in Fig. 4.

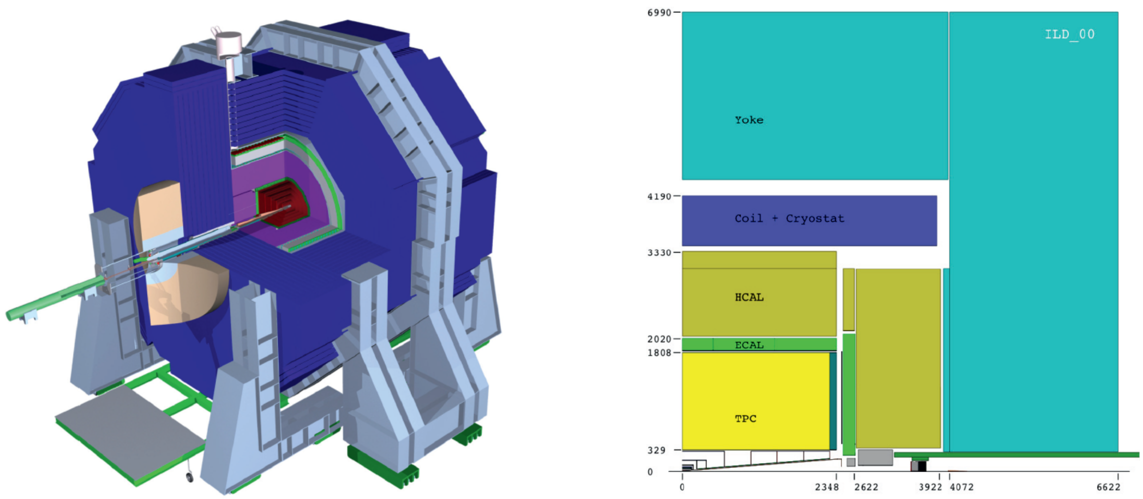

Figure 4: (left) isometric view of SiD ; (right) elevation schematic of ILD.

The physics benchmark studies have been carried out through full simulations of the detectors and supporting structures, including the PFA algorithms tuned to test beam measurements and inclusion of the backgrounds. Excellent performance has been demonstrated, as indicated in Fig. 5 for the Higgs boson branching fraction determinations.

We have argued here that the study of the Higgs boson will be the next major exploration in elementary particle physics, the most direct route that we have now to answering the questions of the TeV energy scale. The ILC experiments will reveal the Higgs boson in high-precision, low-background observations that encompass all of the major couplings of this particle. It is these experiments that will truly bring the Higgs boson to light and shed light on models of higher mass scales.

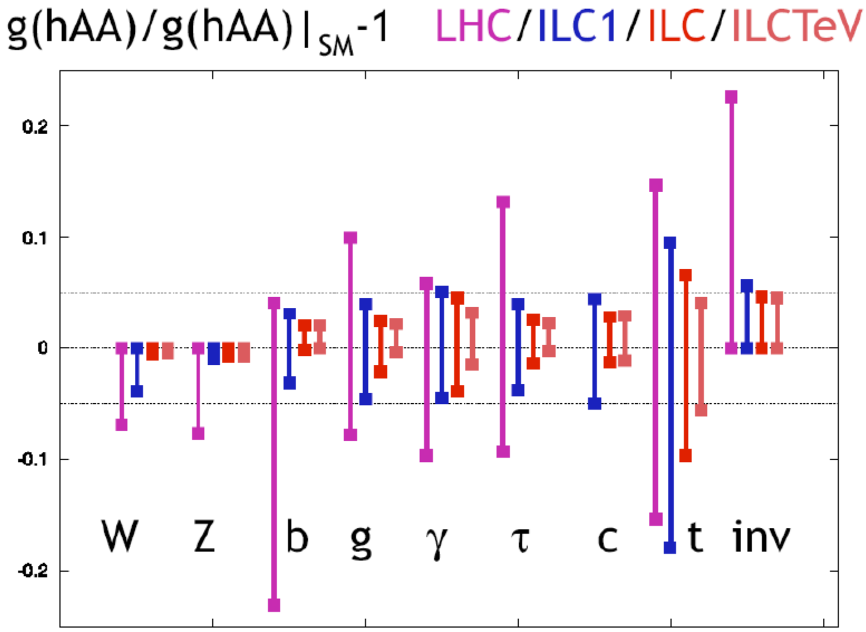

Figure 5: Comparison of the expected measurements on the ratio of measured couplings for Higgs boson branching fractions into various final states, relative to the SM values, for one LHC experiment with 300 fb^{-1}, and the ILC at 250, 500 and 1000 GeV with data accumulations of 250 fb^{-1}, 500 fb^{-1} and 1000 fb^{-1} respectively. For the four data points in each decay channel, a succeeding generation measurement includes also all the previous measurements. The symbol "inv" indicates limits on the coupling to invisible decay modes of the Higgs; the final 95% CL limit on the branching ratio is 0.3%. The plot is taken from M. Peskin, arXiv:1207.2516 [hep-ph].