Chapter 11 Interaction Regions

1 Introduction

The Standard Model has received considerable experimental attention in the past two decades, and much is known about its electroweak sector and about its flavor sector. Recent precision experiments have the sensitivity to look beyond the SM for new physics. However, the mechanism for symmetry breaking in the SM is still unknown, and many questions, such as the existence of SUSY, still are answered only by speculation. A future linear collider will provide the tools with which we may probe the mechanism of symmetry breaking and address the questions of new physics beyond the SM. We seek the best configuration of a linear collider facility that maximizes the potential for answering these questions.

The number of interaction regions is a very important issue, affecting the project cost, the physical footprint of the collider complex, the number of detectors that can be accommodated, the breadth of the physics program, and almost certainly the amount of enthusiasm and support the linear collider would receive in the world's high energy physics community. In this section we look at the nature and number of interaction regions to accompany the accelerator complex of a linear collider. The baseline configurations for TESLA and the NLC are briefly discussed here. This section gives only a brief overview of the technical designs. One must go to the relevant reports and documents to get more technical details.

Both the TESLA and the NLC designs for the IRs allow for two regions. The TESLA philosophy in its baseline design differs somewhat from that of the NLC. The baseline design for TESLA includes only one IR, with real estate available for a second IR and a second beam delivery system, if and when the funds become available. The NLC baseline design contains two IRs, as described below.

The arguments favoring the two-IR collider configuration come first from the physics program. The rich program of particle physics could best be investigated by two active IRs with two or more detectors. However, one must consider the trade-off between the increased breadth of the physics program and the increased costs incurred. One of the "costs" encountered is the unavoidable sharing of the available luminosity between the two IRs. Strategies for simultaneous running in the NLC are briefly discussed.

However, it should be pointed out that the strongest motivation for two IRs may come from external factors. The future linear collider will surely be an international facility. In order for there to be international participation in the financing of the collider, it would be wise to incorporate two IRs to facilitate broad participation in the detectors and the experimental program. This philosophy on international participation in the linear collider is surely part of the strategy for incorporating two IRs in the TESLA and NLC designs.

2 The two interaction region design at TESLA

TESLA has provision for two IRs, one which is in the baseline design, and a second which is not currently in the baseline, but may be added. The TESLA linear collider cannot serve two IRs with luminosity simultaneously. It is possible, however, to switch the beam between the two experimental stations. The primary IR will receive beams at a zero crossing angle, while the secondary IR will have a crossing angle of 34 mrad. If the secondary IR is run in the e^+e^- collider mode (with crab crossing), it is anticipated to have the same luminosity as the primary IR. The crossing angle also makes the secondary IR suitable for $\gamma\gamma$ and $e\gamma$ collider modes of operation using backscattered laser beams, as described in Chapter 13. Electron-electron collisions are possible at one or both IRs, by reversing magnet polarities and providing a second polarized electron source. This option is discussed in Chapter 14. The layout of the two IRs and their technical parameters can be found in the TESLA TDR [1].

3 The dual-energy interaction region design at the NLC

To allow for a collider design for the desired physics program that extends from the Z-pole to many TeV, the NLC group has introduced a dual-energy IR design [2]. The first IR is in a direct line with the main linacs that accelerate the beams. The second IR is reached by bending the beam away from this direct line. Both IRs have crossing angles, as described below. The IRs would be designed to operate in different energy ranges, the first from 250 to 1000 GeV, the second from 90 to 500 GeV.

There are two motivations for this choice. First, by having one of the two IRs in a direct line with the main linacs that accelerate the beams, this IR can operate at multi-TeV energies in subsequent machine energy upgrades. This layout eliminates the bending where incoherent synchrotron radiation would dilute the beam emittances. Second, Final Focus beamlines are naturally optimized to operate over roughly a factor of four to five in beam energy. At the high end of the range, the luminosity decays rapidly due to increasing synchrotron radiation. At lower energies, the luminosity scales proportionally to the collision energy until a limit is reached at roughly 25% of the maximum energy. Below this limit, the luminosity decays as the square of the collision energy due to increasing aberrations and limited vacuum and masking apertures. At either end, a smoother dependence of luminosity on energy can be retained by realigning the Final Focus components to change the total bending.

The choices we have indicated, with two Final Focus systems of fixed configuration, give the NLC overlapping coverage of the energy region that is thought to be initially of interest.

Because the straight-ahead IR could support multi-TeV beam collisions, we refer to this as the 'high-energy' IR (HEIR). The bending required to reach the second IR limits the maximum energy attainable. Thus, we refer to this as the 'low-energy' IR (LEIR). Schematic plans of the NLC machine and the two-IR layout are shown in Figs. 11.1 and 11.2.

With this starting point, the collider layout is determined by the length of the beam delivery systems, the required transverse separation of the IRs, and the desired crossing angle in the interaction regions. Given the new Final Focus optics design which utilizes local chromatic correction, the Final Focus can be relatively short. The present NLC Final Focus design is 700 meters long. This length is sufficient up to 5 TeV in the center of mass. In addition to the Final Focus optics itself, there are diagnostic regions and beam collimation regions upstream of the IP. Depending on the operating mode, these regions could likely be shared. In the present NLC design, these regions are roughly 1300 meters long for a total beam delivery system length of 2 km per side. This length could be reduced; however it is relatively inexpensive and provides a conservative solution to the beam optics and the beam collimation problems.

To attain reasonable transfer efficiency of the rf to the beam in a normal conducting linear collider, the bunches must be spaced together very closely. In this case, both IRs must have a non-zero crossing angle to prevent interactions between bunches at satellite crossings. Typical values for the crossing angle could range from 6 mrad to 40 mrad. The larger angles result in easier beam extraction and IR integration but lead to more difficult tolerances. Simplifying the beam extraction is important if one believes that it is important to measure the beam energy spread and polarization after collision at the IP. The crossing angles allow for these measurements in the NLC but not at the primary IR at TESLA.

Without consideration of the extraction line, the minimum crossing angle is set by the 'multi-bunch kink' instability. At CM energies below 1.5 TeV, the minimum angle in a normal conducting design is roughly 2 mrad. However, studies of the CLIC 3 TeV IR suggest that a minimum crossing angle of 15 mrad is necessary at multi-TeV energies. For these reasons, a crossing angle of 20 mrad at the HEIR and between 20–40 mrad at the LEIR is suggested.

The IR halls have been sized assuming that one would house the NLC L or SD Detector and that one would house the P Detector. Table 11.1 gives a list of the hall parameters. The hall length (transverse to the beam) is large enough to allow assembly of the detector while a concrete wall shields the interaction point. The wall would also serve as radiation shielding if the detector is not deemed to be 'self-shielding'. If the detector were built in place on the beam line, and could be self-

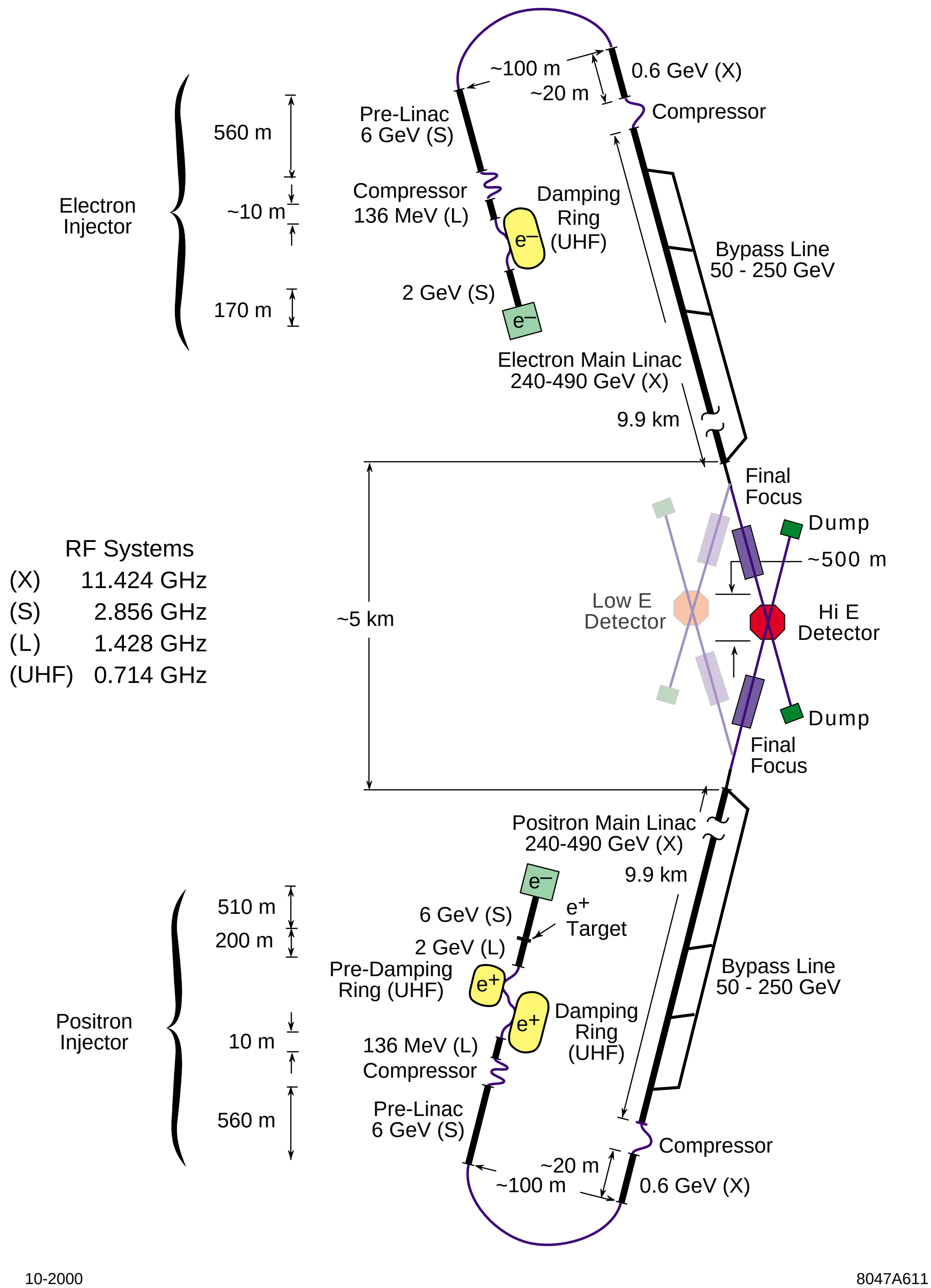

Figure 11.1: Schematic of the non-zero crossing angle of the two linacs and the Dual Energy IR layout.

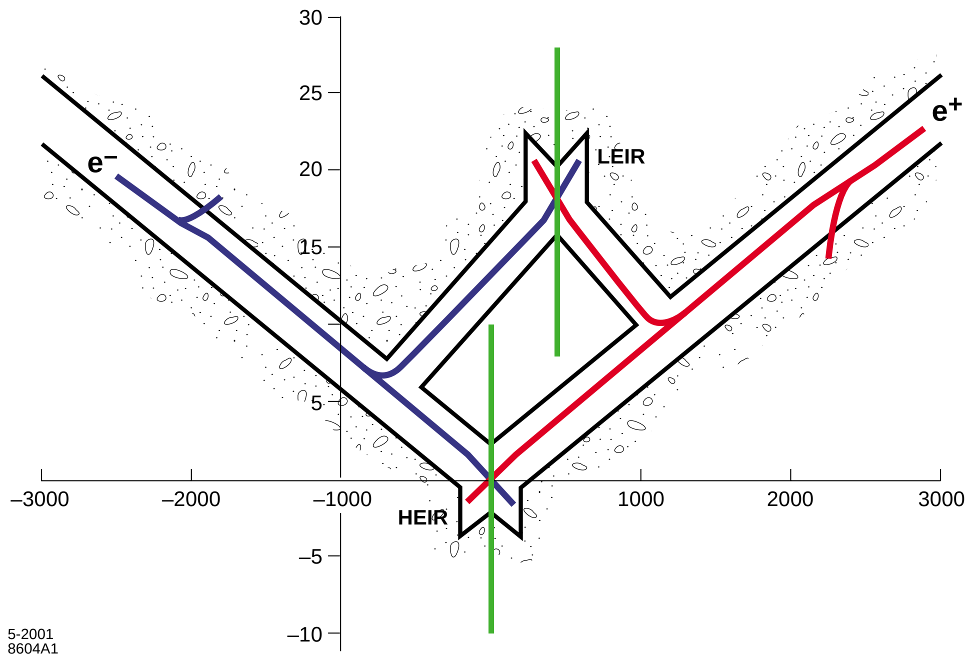

Figure 11.2: Schematic of the accelerator tunnels leading to the two interaction regions. The IRs are separated laterally by 25 m and longitudinally by 440 m. The crossing angles at the HEIR and LEIR are 20 mrad and 30 mrad, respectively. Note that the figure is extremely compressed in the horizontal direction; the detectors occupy the volume of the vertical rectangles that intersect the two beamlines at their crossing points.

shielding, the length could be reduced by roughly a factor of three. The hall width (parallel to the beamline) is set by the constraint that the doors open just enough to allow servicing of the inner detectors.

The baseline design assumes that the two IR halls are physically separated so that activities and mechanical equipment operating in one hall are seismically isolated from the other hall. For example, the LIGO facility has used 100 m as a minimum separation between rotating machinery and sensitive detectors. While the active detection and compensation of culturally induced ground vibration is a key element of the NLC R&D program, passive compliance with vibration criteria is the ideal. In principle each of the IR halls could be designed to accommodate two detectors that share the beamline in a push-pull manner, thus increasing experimental opportunities, or the overall NLC layout could be changed to support only one push-pull IR at a considerable cost savings. In any push-pull scheme, major installation activities might need to be curtailed if they introduced uncompensated vibration of the final magnets producing data for the detector currently on the beam line.

All of these features are illustrated in the schematic designs shown in Figs. 11.1 and

Parameter	Small Detector	Large Detector
Detector footprint	12 × 11 m	20 × 20 m
Pit length	40 m	62 m
Pit width	20 m	30 m
Pit depth below beamline	5 m	7 m
Door height	10 m	13 m
Door width	10 m	13 m
Barrel weight	2000 MT	7300 MT
Door weight	500 MT	1900 MT
Total weight	3100 MT	11100 MT

Table 11.1: The Baseline Interaction Region Parameters

11.2. The main linacs are aligned to provide the 20 mrad crossing angle at the HEIR. The LEIR beamline is bent from the straight-ahead beams. The transverse separation between the two IR collision points is currently set at roughly 25 meters. However, roughly 440 meters longitudinal separation of the two IR halls has been provided for increased vibration isolation. In addition, bypass lines are installed along the side of the linac so that lower-energy beams can be transported to the Final Focus without passing through the downstream accelerator structures.

3.1 The low-energy interaction region at the NLC

The experimental program in the LEIR is determined by the range of accessible center-of-mass energies and the available luminosity. The amount of luminosity that should be dedicated to a particular $\sqrt{s}$ will depend on the physics that is revealed by the Tevatron and the LHC. This need for flexibility imposes the requirement that the LEIR have high performance at least over the range $m_Z \leq \sqrt{s} \leq 2m_t$. Figure 11.3 shows the luminosity for the baseline design of the LEIR versus the center-of-mass energy. In the following, we outline the basic LEIR physics program as a function of increasing beam energy.

The lowest operating energy of the LEIR is determined by the requirement that high-statistics studies at the Z-pole be possible. The goal of a next-generation Z-pole experiment would be a significant reduction in the experimental errors in key electroweak parameters, as explained in Chapter 8. The success of this program relies on the availability of longitudinally polarized beams. Polarized electron beams will be available in the initial configuration. It would be desirable eventually to have positron polarization as well. Issues and technologies for positron polarization are discussed in Chapter 12. One feature pertaining to beam polarization in the LEIR is the need to account for the spin precession in the bends in the beam transport system. Another

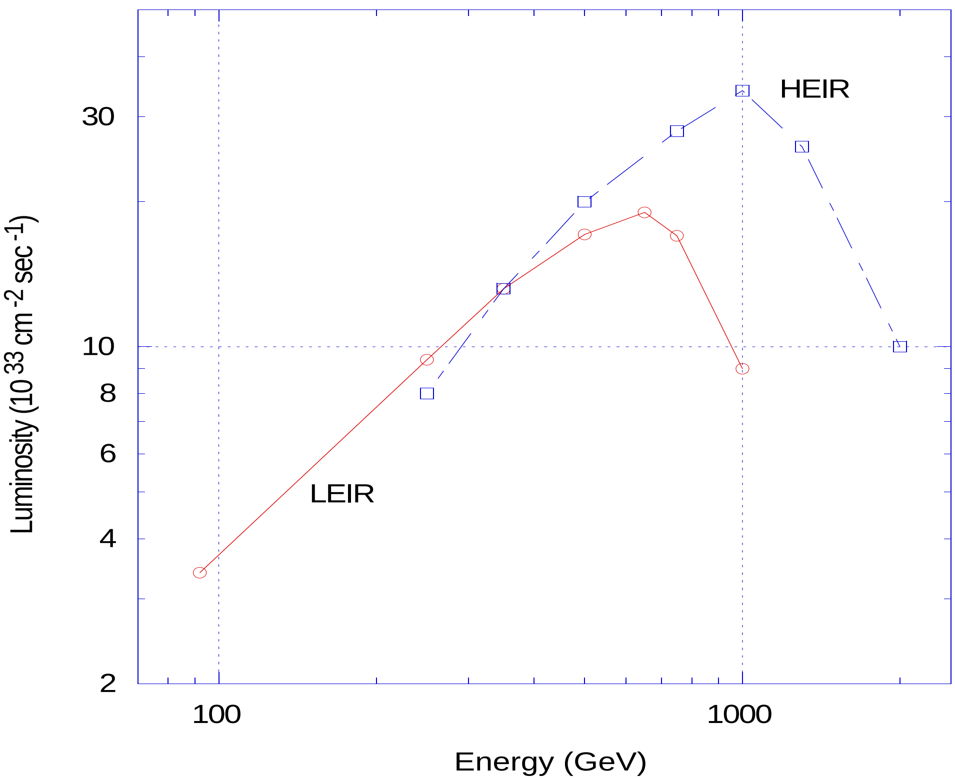

Figure 11.3: The baseline luminosity versus CM energy for the NLC LEIR and HEIR. The two IRs have been designed to have comparable performance in the region between 250 GeV and 500 GeV, however, the NLC HEIR beam delivery system has been optimized for a maximum energy of 500 GeV, the HEIR for 1 TeV.

issue is the desire to account for the depolarization that arises during collision. For this reason, a crossing angle is desirable, since it eases the polarization measurement after the IP.

Precise determination of the electroweak parameters could be particularly valuable in understanding the SM and physics beyond, particularly at a time when the Higgs boson mass is experimentally determined. In the event that only a single Higgs boson is observed with no other direct evidence of new physics from the LHC programs, the precision electroweak measurements will be a crucial aspect of the NLC program. A benchmark for such a program would be to accumulate a sample of 10^9 Z^0 decays.

The W-pair threshold occurs near $\sqrt{s} = 160$ GeV with the maximum production cross section at $\sqrt{s} \sim 200$ GeV. In the event that a significantly improved measurement of the W mass is required, it will be necessary to have dedicated running at the W-pair threshold. Studies have shown that an error on the W mass of 6 MeV would be obtainable with 100 fb^{-1}. Given the otherwise very limited physics program in this energy range, the need for high instantaneous luminosity is evident.[1]

Beyond the W-pair threshold, it is highly likely that next benchmark center-of-mass energy will be the production cross section peak for a light Higgs boson. Precise measurements of the Higgs mass, width, spin-parity, and branching fractions are essential to help understand the role this object would play in electroweak symmetry breaking. The associated production process $e^+e^- \to Z^0h^0$, with $Z^0 \to \ell^+\ell^-$ and ℓ an electron or muon, provides a model-independent tag of Higgs production. The Higgs signal is easily identifiable in the dilepton recoil mass distribution. The maximum cross section for associated production occurs at roughly $m_Z + \sqrt{2}m_{\rm h}$. In minimal SUSY, the mass of the lightest CP-even scalar is required to satisfy $m_h \lesssim 135$ GeV. The precision electroweak fit to the SM calls for a Higgs boson with mass below 200 GeV. It is therefore essential that the LEIR design be capable of delivering high luminosity in the range $220 \lesssim \sqrt{s} \lesssim 340$ GeV. The study of a light Higgs boson will also benefit from control of the beam polarization; for example, for the measurement of the hWW coupling, one can exploit the large difference in the $\nu\overline{\nu}h^0$ production cross section for e^-_L and e^-_R beams. For some processes, positron polarization is also desirable. In many scenarios, the precision study of a light Higgs boson would be the principal focus of the LEIR program.

The $t\overline{t}$ threshold occurs near 350 GeV. The low-energy IR would be the natural facility to focus on this important topic. The threshold onset is a difficult process to study experimentally because of the resolution smearing caused by the natural energy spread from bremsstrahlung in the initial state, and from energy spread in the linear collider. The amount of dedicated running at the $t\overline{t}$ threshold will be dictated by the Higgs physics program. If a light Higgs is present, $m_H \lesssim 180$ GeV, it may be desirable to run below the $t\overline{t}$ threshold to control physics backgrounds and to optimize the Higgs production rate. For the case where the physics of electroweak symmetry breaking has conspired to produce a heavy Higgs boson that somehow satisfies the precision constraints, the study of the top quark properties will assume a central importance. The integrated luminosity requirements for the LEIR at or above the $t\overline{t}$ threshold in such a scenario will be the order of 100 fb^{-1} necessitating instantaneous luminosities of at least 5×10^{33} cm^{-2}s^{-1}.

Other physics options for the low-energy IR have been considered extensively. The region would serve well as the location for a 'second generation' detector for $\gamma\gamma$ collisions. Similarly, an e^-e^- program might be done in the LEIR, should the physics motivations lead in this direction.

In summary, a low-energy IR has many uses and advantages in an NLC program. It would provide considerable flexibility in the physics program, and would preserve many physics opportunities in scenarios in which the NLC is upgraded to multi-TeV

[1]Although investigation of W-boson properties will be an important goal of any NLC program, many of these studies, *e.g.*, the determination of Triple Gauge Boson couplings, are best performed at the highest achievable center-of-mass energy. This issue is discussed in Chapter 5, Section 2.

operations for high-energy studies in the other IR region.

3.2 The high-energy interaction region at the NLC

The design of the NLC allows for an IR region capable of upgrading to multi-TeV operations in an energy-upgraded NLC. To assure this possibility, the beam delivery systems are aligned in a straight-ahead configuration relative to their respective linacs, with very little bending of the incoming beams between the linear accelerator structure and the IR. To preserve the non-zero crossing angle required at the point of collisions, the two halves of the collider structure are not parallel but rather cross at an angle at the collision point. Figure 11.3 shows the luminosity versus CM energy for the baseline design of the HEIR.

The HEIR physics program is intimately related to the scenario that is realized in Nature for electroweak symmetry breaking. In the event that supersymmetry is discovered, the focus of the HEIR program will be the measurement of sparticle properties. It is unlikely that the full SUSY spectrum will be accessible at $\sqrt{s} = 500$ GeV; therefore, the energy reach of the HEIR should be upgradable to the multi-TeV region. Symmetry-breaking arising from some new strong dynamics would also be likely to put a premium on the energy reach. It is clear that in comparison to the LEIR, the physics requirements for the HEIR are, to first order, straightforward: the highest possible luminosity at the highest possible energy.

The energy span of the HEIR runs from 250 GeV to 500 GeV in the initial phase. Therefore the physics program can in principle include everything from 250 GeV on up, a region which overlaps in energy with the LEIR. Studies of W-pairs, low-lying SUSY states, and the $t\bar{t}$ threshold could occur in the HEIR. Although, in the case of a light Higgs boson, much of the precision Higgs physics could be performed at the LEIR, there is Higgs physics unique to the HEIR. For a light Higgs boson consistent with the current theoretical and experimental constraints, the maximum cross section for the rare process $e^+e^- \to Z^0h^0h^0$ occurs at $\sqrt{s} \sim 500$ GeV. This process is of great interest, since it enables measurement of the Higgs self-coupling which in turn can be related to the shape of the Higgs potential. The W-fusion process, $e^+e^- \to \nu\bar{\nu}h^0$, which is sensitive the hWW vertex, has a cross section that increases with center-of-mass energy. The measurement of the Higgs self-coupling sets a benchmark for the accelerator performance. Depending on the exact mass, a measurement of this quantity requires integrated luminosities the order of 1000 fb^{-1}, which corresponds to 3–4 years at design luminosity.

Supersymmetry is a primary candidate for physics beyond the SM. Almost all versions of SUSY models result in low-lying states that would appear in e^+e^- annihilations below 500 GeV. Although the discovery phase for SUSY is likely to occur at the Tevatron or LHC, the NLC will play a key role in the detailed study of the sparticle spectrum and subsequent delineation of the soft SUSY-breaking Lagrangian.

To exploit fully the physics potential of the NLC, a number of special operating conditions may be necessary for the HEIR. For example, in EWSB models with extended Higgs sectors, of which SUSY is the most widely studied, a $\gamma\gamma$ mode of operation for the HEIR may be crucial. For example, the $\gamma\gamma$ mode enables production of a single Higgs boson; for the case of a nominal 500 GeV center-of-mass, this would effectively increase the mass reach from 250 GeV to 400 GeV for production of heavy neutral Higgs particles. Operation with transversely polarized photon beams allows separate production of the CP-even and CP-odd states. Control of the electron and positron beam polarization will also be extremely useful. For Higgs physics it can be used to increase the nominal production cross section for the self-coupling measurement. Beam polarization will also be useful in unraveling gaugino and slepton mixing. The need for an e^-e^- operating mode may be necessary to decipher selectron production.

It is likely and perhaps desirable that there be a staged evolution of the HEIR center-of-mass energy. Although the goal of the initial phase of the NLC is 500 GeV for the HEIR, it may be possible to start physics earlier at a lower collision energy. An intermediate commissioning stage with $\sqrt{s} \sim 250$ GeV and modest luminosity could potentially be very relevant and exciting, especially if direct evidence from the LHC indicated the production of a light Higgs boson or a threshold for supersymmetric states. Another obvious commissioning stage could be the $t\bar{t}$ threshold at 350 GeV. Even at 10% of design luminosity, the physics program promises to be rich. For example, dedicating 10 fb^{-1} to a scan of the $t\bar{t}$ threshold would already lead to a top quark mass measurement with a 200 MeV error, as discussed in Chapter 6, Section 2.

3.3 Alternative interaction region scenarios

The baseline scenario that we have assumed considers two interaction regions—a high-energy region limited only by the available accelerating structures and a second region that is limited in energy or by the support of $\gamma\gamma$ or other options. It is appropriate to discuss alternative scenarios and the interplay between the physics programs of the high- and low-energy interaction regions. The issue is complicated by the diversity of physics scenarios that may arise. An additional consideration is the possible staging of the maximum center-of-mass energy. The possibilities can be broadly classified into types:

a) Single interaction region with one detector;

b) Single interaction region with two detectors;

c) Two interaction regions, high-energy and low-energy;

d) Two high-energy interaction regions.

For scenario (a), there is an obvious cost advantage; however, the NLC physics program could be unduly compromised. The physics program would be tightly coupled to the available center-of-mass energy. Depending on the details of the actual physics scenario, it may not be possible to simultaneously satisfy the various needs of a diverse user community. The resolution of mutually exclusive requirements for luminosity and choice of the center-of-mass energy may not be straightforward.

It is difficult to identify the merits of scenario (b), given the limitations of a single IR outlined above for scenario (a). Given that the total luminosity accumulated by both experiments will be comparable to that for a single experiment, this scenario would only be of interest if the two detectors were of sufficiently different capabilities or there were very strong sociological arguments for a second collaboration. One possible scenario where differences between detectors could arise is if there were a need to have a dedicated $\gamma\gamma$ collider program. In such a scenario, it would be more natural to consider a push-pull capability for one of the IRs in a two-IR facility. The two IR regions allow for a push-pull configuration in a least one of the two regions. The footprint of the push-pull IR hall must not infringe on the beamline of the adjacent region. In addition, access to the detector captured between the two beamlines must be possible, and adequate shielding must be provided to permit work in the IR hall when beams are alive in the machine. Scenarios for staging two detectors would have to be considered and understood. These are complicated issues that would involve assumptions that might not be appropriate at a future date. Nevertheless, provision for staging two detectors in a push-pull configuration would be a low-cost and effective means to keep open future possibilities for a unique and special-purpose detector.

The scenario that has been chosen as the baseline is (c); there are a number of considerations in its favor. It makes it possible to have parallel physics programs running simultaneously, a clearly desirable feature. The upgrade path for the HEIR is less complex. It provides for a lower-energy IR that can be dedicated to precision studies of the Higgs boson, Z-pole or $t\bar{t}$ system. Moreover, in this scenario both the HEIR and LEIR will cover the preferred energy range for the study of a light Higgs. The two-IR design adds a degree of flexibility that enables the NLC to address essentially any physics scenario that could arise.

The scenario (c) affords a natural context for energy staging. As mentioned in Section 2.2, staging the HEIR energy at the beginning of the NLC program would make it possible to perform an initial investigation of the region above 250 GeV. Commissioning of the LEIR program might follow the completion of the full complement of accelerating structures required to reach 500 GeV though, with a bypass line, this might alternatively begin before the accelerator is complete. Many of the high-luminosity measurements foreseen for the LEIR would benefit from longitudinally polarized positron beams, which are not likely to be available at the initial stages of running.

Given the need to have minimal bending in the beam delivery system in order to preserve beam emittances, scenario (d), which has two high-energy IRs of similar performance, becomes technically challenging and more costly. Given the interest exhibited by many members of the physics community in the low-energy potential of the NLC, and the need to perform high-statistics studies of the Z-pole in a number of physics scenarios that could arise, it would seem prudent to have at least one IR capable of delivering that physics.

3.4 Simultaneous operation

The NLC design has in it the capability for simultaneous operations in the two IRs. In the baseline design, the accelerator delivers bunch trains at a rate of 120 Hz. With pulsed magnets, the beams can be sent alternately to two IRs, resulting in an even split of 60–60 Hz. Uneven splitting of the 120 pulses per second is technically more challenging, and is not envisioned as an option.

A higher pulse rate in the NLC is possible, but is not in the baseline design. It appears technically feasible, for example, to operate at 180 Hz. This would require modifications to the damping rings and additional cooling for the klystrons and modulators in some regions of the accelerator. But these changes would allow operation, for example, with 60 Hz of low-energy beams in the LEIR and 120 Hz of beams in the HEIR. This mode of operation would clearly enhance the experimental program and augment the total luminosity delivered to the experimenters.

References

[1] TESLA Technical Design Report, http://tesla.desy.de/new__pages/TDR__CD/start.html

[2] US NLC Collaboration, *2001 Report on the Next Linear Collider*, FERMILAB–Conf–01/075–E, LBNL–47935, SLAC–R–571.