Chapter 12 Positron Polarization

1 Introduction

The baseline designs for NLC and TESLA include a polarized electron beam, but the positron beam is unpolarized. In this chapter, we investigate the physics merits of positron polarization and summarize the status of proposed polarized positron source designs. These questions have also been discussed in [1].

The importance of electron beam polarization has been demonstrated in Z^0 production at the Stanford Linear Collider (SLC), where 75% 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. In particular, it allowed the SLD experiment to make the world's best measurement of the weak mixing angle, which is a key ingredient for indirect predictions of the SM Higgs mass. The electron polarization at SLC also provided a powerful tool for bottom quark studies, providing a means for b and $\overline{b}$ tagging from the large polarized forward-backward asymmetry, and for studies of parity violation in the $Zb\overline{b}$ vertex. At a 500 GeV linear collider, electron polarization will increase sensitivity to form-factor studies of W^+W^- and $t\overline{t}$ 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.

But what will positron polarization add? First, the presence of appreciable positron polarization is equivalent to a boost in the effective electron polarization. Measured asymmetries that are proportional to the polarization will increase; fractional errors in these quantities will accordingly decrease. Second, cross sections for many processes will grow. Any process mediated by gauge bosons in the s-channel naturally wastes half the incident positrons. Left-handed electrons, for example, only annihilate on right-handed positrons. The same is true for t-channel exchanges with unique handedness in their couplings, such as neutrino exchange in W-pair production. By polarizing the positrons and coordinating their polarization with that of the electrons, the cross sections for these processes can double (in the limit of 100% polarization). Finally, polarimetry will benefit from positron polarization. As the effective polarization increases, its error decreases, allowing measurements with very small systematic errors. Such small errors are needed for high-precision work at the Z pole and will benefit studies of production asymmetries for W^+W^-. And, by using measurements of rates with all four helicity states (RL,LR,RR,LL) the beam polarizations can be inferred directly without additional polarimetry.

What positron polarization can bring, poor yields of polarized positrons can take away, so the yield of any source of polarized positrons is very important. Several schemes have been advanced for polarizing positrons. All are ambitious, large systems which are mostly untested. R&D is required before decisions are made about how and when to include positron polarization in linear collider design.

2 The physics perspective

2.1 The structure of electroweak interactions at high energies

The primary purpose of a linear collider will be to study the mechanism of electroweak symmetry breaking (EWSB). Beam polarization at a high-energy linear collider can play an important role in this endeavor because: (1) the electrons and positrons in the beams are essentially chirality eigenstates; (2) gauge boson interactions couple $e^-_L e^+_R$ or $e^-_R e^+_L$ but not $e^-_L e^+_L$ or $e^-_R e^+_R$; and (3) the $SU(2)_L$ interaction involves only left-handed fermions in doublets, whereas right-handed fermions undergo only hypercharge $U(1)_Y$ interactions. At typical LC energies, where masses are small compared to $\sqrt{s}$, one can replace the exchange of γ and Z bosons with the B and W^3 bosons associated with the unbroken $U(1)_Y$ and $SU(2)_L$.

As a concrete application of these points, consider $e^+e^- \to W^+W^-$ production, which is a background to many new physics searches. There are three tree–level Feynman diagrams for this process, one involving the t-channel exchange of ν_e and the others involving the s-channel exchange of γ and Z. The polarization choice $e^+e^-_R$ will eliminate the first contribution, since W bosons have only left-handed interactions. Decomposing the s-channel diagrams into a W^3 and a B contribution, the W^3 diagram is also eliminated using e^-_R polarization for the same reason. The only remaining diagram now vanishes for symmetry reasons—the B and W bosons involve different interactions and do not couple to each other. In reality, there is a small but non-vanishing component to W^+W^- production, because of EWSB. The polarization choice e^+_R would eliminate this background at tree-level. Of course, it also important to consider the behavior of the signal process under the same choices of polarization and the fact that 100% beam polarization is difficult in practice.

In the example above, note how the polarization of only one beam had a dramatic effect. Once the electron polarization was chosen, only certain positron polarizations contributed. One can imagine also the case where the desired effect is to enhance the W^+W^- signal. Then, by judiciously choosing the polarization combination $e^-_L e^+_R$, the production rate is enhanced by a factor of four relative to the unpolarized case, and a factor of two beyond what is possible with only electron polarization. When either searching for rare processes or attempting precision measurements, such enhancements of signal and depletions of background can be quite important.

We use the convention that the sign of polarization is *positive* for *right-handed* polarization, both for electrons and for positrons. Then, for example, for the case of single gauge boson production, the production cross section is proportional to

$$(1-\mathcal{P}_-)(1+\mathcal{P}_+)c_L^2 + (1+\mathcal{P}_-)(1-\mathcal{P}_+)c_R^2, \tag{12.1}$$

where c_L and c_R are chiral couplings. Equation (12.1) is at the heart of the forward-backward asymmetry that arises when $c_L \neq c_R$. If two measurements of the cross section are made with a different *sign* for the polarizations $\mathcal{P}_-$ and $\mathcal{P}_+$, then the difference of the two measurements normalized to the sum is:

$$\frac{N_L - N_R}{N_L + N_R} \quad = \quad \mathcal{P}_{\rm eff}\frac{c_L^2 - c_R^2}{c_L^2 + c_R^2} \quad \equiv \quad \mathcal{P}_{\rm eff} A_{LR}, \tag{12.2}$$

where

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_- - \mathcal{P}_+}{1 - \mathcal{P}_-\mathcal{P}_+} \ . \tag{12.3}$$

In Z boson production, A_{LR} depends on the difference between $1/4$ and $\sin^2\theta_W$. Since the error in an asymmetry A for a fixed number of events $N = N_L + N_R$ is given by $\delta A = \sqrt{(1-A^2)/N}$, increasing $\mathcal{P}_{\rm eff}$ makes measurable asymmetries larger and reduces the error in the measured asymmetry significantly if A^2 is comparable to 1. When only partial electron polarization is possible, a small positron polarization can substantially increase $\mathcal{P}_{\rm eff}$, while also decreasing systematic errors. These asymmetry improvements utilizing polarized positrons are exploited in the Giga-Z mode for a linear collider. With Giga-Z, polarized positrons are needed to take full advantage of the large statistics possible at a linear collider—50 times more data than the integrated LEP-I data sample and 2000 times more data than SLD's sample. With a Giga-Z data sample, one expects to achieve a factor of 20 improvement over SLD's A_{LR} and A_b measurements. These improved measurements can be used to perform exquisite tests of the Standard Model. Together with a precise measurement of the top quark mass (to 100 MeV from a threshold scan at a linear collider), the A_{LR} measurement can be used to predict the Standard Model Higgs mass to 7%. The Giga-Z program is discussed in more detail in Chapter 8.

Equation (12.1) is also applicable to other situations. In general, as long as a process has a helicity structure similar to that of s-channel gauge boson production, the rate is

$$(1-\mathcal{P}_-\mathcal{P}_+)\sigma_{\rm unpol}\left(1 + \mathcal{P}_{\rm eff}\frac{c_L^2 - c_R^2}{c_L^2 + c_R^2}\right), \tag{12.4}$$

where $\sigma_{\rm unpol}$ is the unpolarized cross section. Notice that polarization can increase the cross section by at most a factor of four, as can occur for W^+W^- production where $c_R \simeq 0$.

2.2 Standard Model-like Higgs boson

One process of particular interest for a LC is Higgs boson production. The primary modes at a LC are associated production with a Z boson (Zh) and vector boson fusion ($\nu\overline{\nu}h$). The Zh process is particularly simple, since the direct coupling of the Higgs boson to electrons is negligible. Polarization effects appear only at the initial e^+e^-Z vertex. The Z process allows for the discovery and study of a Higgs boson with substantial couplings to the Z boson independently of the Higgs boson decay mode, using the Z recoil method. Therefore, the relative size of signal and background is of great interest.

		$\sigma(Zh)$ $c_L^2 = .58$ $c_R^2 = .42$		$\sigma(ZZ)$ $c_L^2 = .65$ $c_R^2 = .35$		$\sigma(W^+W^-)$ $c_L^2 \simeq 1$ $c_R^2 \simeq 0$	
$\mathcal{P}_-$	$\mathcal{P}_+$	$E = 1$ $P = 1$	$E = .8$ $P = .6$	$E = 1$ $P = 1$	$E = .8$ $P = .6$	$E = 1$ $P = 1$	$E = .8$ $P = .6$
0	0	1	1	1	1	1	1
$+E$	0	0.84	0.87	0.69	0.75	0	0.2
$-E$	0	1.16	1.13	1.31	1.25	2	1.8
$+E$	$-P$	1.68	1.26	1.37	1.05	0	0.08
$-E$	$+P$	2.32	1.70	2.62	1.91	4	2.88

Table 12.1: Behavior of various Standard Model cross sections relevant for Higgs boson studies as a function of polarization for full and partial electron and positron polarization. The numbers listed are normalized to the unpolarized cross section.

At tree-level, the Zh cross section depends on polarization as indicated in Eq. (12.1) with the couplings $c_L = -\frac{1}{2} + \sin^2\theta_w$, $c_R = \sin^2\theta_w$. Numerically, the two squared coupling factors appear with the relative weights (normalized to unity) 0.58 to 0.42. Table 12.1 shows the relative behavior of the Zh cross section for full (100%) and partial electron (80%) and positron (60%) polarization. Even for partial polarization, a substantial increase to the production cross section occurs over the unpolarized case. Other Higgs boson production processes, such as $e^+e^- \to HA$ in the MSSM or $e^+e^- \to Zhh$ in the SM or MSSM (relevant for measuring the Higgs self-coupling), proceed through the Z resonance and have the same chiral structure.

Significant backgrounds to the Zh search can arise from W^+W^- and ZZ production. The polarization dependence of these processes is also shown in Table 12.1. The physics of the W^+W^- background was discussed previously. It is relevant to note from Table 12.1 that without full polarization—which may be difficult to obtain in practice—the W^+W^- background cannot be fully eliminated. On the other hand, the partial polarization of both beams can approximately recover the benefits of full polarization, since the effective polarization $\mathcal{P}_{\text{eff}}$ is close to 1. Another potential background, ZZ production, has a similar behavior as the signal Zh, except that an additional Z must be attached to the incoming e^+e^-. Therefore, the relative weight of the different polarization pieces goes as the square of those for Zh production. For the case of partial polarization of both beams and ($\mathcal{P}_- = +80\%, \mathcal{P}_+ = -60\%$), where the W^+W^- background is substantially decreased, there is a small increase in $\sigma(Zh)/\sigma(ZZ)$. The efficacy of polarization will depend on the most significant background. Note that for a Higgs boson mass that is significantly different from m_Z, propagator effects and non-resonant diagrams need to be included, but the results should not be significantly different from those shown here.

The other Higgs production process of interest is WW fusion, which has a similar behavior to the WW background. When operating at energies where Zh and WW fusion are comparable, polarization can be used to dial off the fusion contribution. This may be important for the study of inclusive Higgs production using the recoil technique.

2.3 Supersymmetric particle production

The production and study of new particles with electroweak quantum numbers should be the forte of a linear collider, where the major backgrounds are also electroweak in strength. Supersymmetry is a concrete example of physics beyond the SM that predicts a spectrum of new electroweak states related to the SM ones by a spin transformation. We now discuss some aspects of supersymmetry measurements affected by beam polarization. For further discussion of supersymmetry mass and coupling measurements, see Chapter 4.

2.3.1 Slepton and squark production

One of the simplest sparticle production processes to consider is $\widetilde{\mu}$ pair production, where the interaction eigenstates $\widetilde{\mu}_R$ and $\widetilde{\mu}_L$ are expected to be nearly mass eigenstates. Gauge bosons couple to the combinations $\widetilde{\mu}_R\widetilde{\mu}_R^*$ and $\widetilde{\mu}_L\widetilde{\mu}_L^*$. $\widetilde{\mu}_R$ has only couplings to the hypercharge boson B. The initial e^+e^- state has different hypercharge depending on the electron polarization: e_L^- has $Y = -1/2$, whereas e_R^- has $Y = -1$. The production cross section depends on Y^2 and thus is four times larger for e_R^- than for e_L^-. Furthermore, the choice e_R^- significantly reduces the background from W^+W^- production, which comes both from decays to $\mu^+\nu_\mu\mu^-\overline{\nu}_\mu$ and from feed-down from decays to τ. Since $e_R^-e_R^+$ components do not contribute to the signal, left-polarizing the positron beam doubles the signal rate. $\widetilde{\mu}_L$ pair production depends on both B and W^3 (γ and Z) components. Switching the electron polarization will emphasize different combinations. In all, a judicious choice of the positron polarization will make more efficient use of the beam, increase the cross section, and suppress the backgrounds.

For third-generation sparticles such as $\widetilde{\tau}$ and $\widetilde{t}$, there may be significant mixing between the mass and interaction eigenstates, leading to new observables. As for the $\widetilde{\mu}$ case, the production cross section itself is sensitive to the electron polarization. However, increased sensitivity to the mixing may be obtained from a measurement of the left-right asymmetry. For $\widetilde{t}$ production, the addition of 60% polarization in the positron beam increases the accuracy of the mixing angle measurement by 25%, while decreasing systematic errors [2]. Of course, the former effect can be achieved with only e^- polarization by increasing the integrated luminosity.

Selectron production may benefit more from positron polarization because of the e^+e^- initial state at a LC. The exchange of neutralinos $\widetilde{\chi}^0$ in the t-channel introduces more structure beyond the s-channel exchange of γ and Z. The processes $e_L^- e_L^+ \to \widetilde{e}_L \widetilde{e}_R^*$ and $e_R^- e_R^+ \to \widetilde{e}_R \widetilde{e}_L^*$ proceed through $\widetilde{\chi}^0$ exchange only. Considering the case that $\widetilde{e}_L$ and $\widetilde{e}_R$ are close in mass, the polarization of both beams can play an essential role in disentangling the different interaction states. For example, $e_L^- e_L^+$ polarization will only produce the negatively-charged $\widetilde{e}_L$ and the positively-charged $\widetilde{e}_R^*$. Switching the polarization of both beams will produce only negatively-charged $\widetilde{e}_R$ and positively-charged $\widetilde{e}_L^*$. Since the endpoints of the lepton spectrum can be used to reconstruct the selectron and neutralino masses, the electrons and positrons yield separate information about $\widetilde{e}_L$ and $\widetilde{e}_R$. Without the positron polarization, one would always have contamination from $\widetilde{e}_L \widetilde{e}_L^*$ and $\widetilde{e}_R \widetilde{e}_R^*$ production. Conversely, the observation of the switch from one species to another with the change in positron polarization would give more weight to the SUSY interpretation of the events. The study of t-channel exchange in selectron production is an important method for studying neutralino mixing, since the components of the neutralinos that are Higgsino-like do not contribute. Therefore, it is valuable to be able to isolate the t-channel exchanges experimentally by using polarization.

2.3.2 Chargino and neutralino production

The study of chargino pair production $e^+e^- \to \widetilde{\chi}^- \widetilde{\chi}^+$ gives access to the parameters M_2, μ, $\tan\beta$, $m_{\widetilde{\nu}_e}$. It is conservative to assume that only the lightest chargino is kinematically accessible. In this case, studies have considered the case of extracting the SUSY parameters from the measurement of cross sections for full $e_L^- e_R^+$ (σ_L), $e_R^- e_L^+$ (σ_R) and transverse (σ_T) polarizations [3]. By analyzing σ_R and σ_L, the two mixing parameters of the chargino sector can be determined up to at most a four-fold ambiguity, provided that the electron sneutrino mass is known and one assumes the supersymmetric relation between couplings in the interaction Lagrangian. The addition of transverse polarization allows the ambiguity to be resolved and gives a handle on the sneutrino mass. The role of *transverse* polarization is to allow interference between two different helicity states so that a product of two mixing factors appears in a physical observable instead of sums of squares of individual mixing factors, resolving the sign ambiguity. Given the measurement of the chargino mass and the mixing parameters, the Lagrangian parameters $M_2, \mu, \tan\beta$ can be determined up to two-fold ambiguity in modulus and a 2π ambiguity in the phase combination $\arg(m_2)+\arg(\mu)$. Such studies need to be redone with more detail, considering partial beam polarization, backgrounds, cuts, and the likely absence of transverse polarization, but there is promise that SUSY parameters can be extracted from real data.

Other investigations have considered the consequences of partial longitudinal polarization at a purely theoretical level, focusing on the case $|\mathcal{P}_-| = .85, |\mathcal{P}_+| = .60$, and studying production cross sections near threshold [4]. Comparing a gaugino-like and Higgsino-like chargino, the total cross sections including the decay $\widetilde{\chi}^- \to e^-\overline{\nu}\widetilde{\chi}^0_1$ are calculated as a function of electron and positron polarization. For an unpolarized positron beam, the cross sections from e^-_L are larger than those from e^-_R for both the gaugino and Higgsino cases. However, the addition of positron polarization gives access to more detailed information. For example, one has the relation that $\sigma(e^-_R e^+_L)$ is less than the unpolarized cross section for gaugino-like charginos, and greater for Higgsino-like charginos. The sensitivity of the forward-backward asymmetry A_{FB} to polarization, and how this effect can be used to bound the sneutrino mass, has also been discussed [5]. Similar considerations can be applied to the case of $\widetilde{\chi}^0\widetilde{\chi}^0$ production. These analyses would benefit from more detailed studies, including backgrounds and addressing the issue of measuring branching ratios.

2.4 Some other new physics

Contact interactions can arise from many sources of new physics, such as compositeness, a heavy Z', leptoquarks, KK excitations, *etc.* The low-energy effect of such physics can be parameterized in an effective Lagrangian as

$$\mathcal{L}_{\text{eff}} = \frac{\tilde{g}^2}{\Lambda_{\alpha\beta}}\eta_{\alpha\beta}(\overline{e}_\alpha\gamma_\mu e_\alpha)(\overline{f}_\beta\gamma_\mu f_\beta), f \neq e, t.$$

The chiral components are extracted by varying $P_{\text{eff}} = \pm P$ (this is just A_{LR}). Positron polarization increases the reach on $\Lambda_{\alpha\beta}$ by $20 - 40\%$ depending on the nature of the couplings [6].

Low-energy signatures of string theory may include spin-zero resonances with non-negligible couplings to the electron and sizable amplitudes [7], *i.e.*, $\mathcal{A}(e^-_R e^+_R \to \gamma^*_{03}) = \sqrt{2}eM_S$ and $\mathcal{A}(e^-_L e^+_L \to \gamma^*_{04}) = \sqrt{2}eM_S$. With positron polarization, the SM backgrounds to these processes should be negligible.

2.5 Transverse polarization

Finally, we should comment on transverse polarization, which has been considered in some chargino studies. Transversely polarized beams are linear combinations of different helicities with equal weight. Transverse polarization can introduce an azimuthal dependence into production cross sections, proportional to the degree of polarization. However, all such effects in the SM are negligible upon azimuthal averaging for an e^-e^+ collider, because of the small electron mass and Yukawa coupling [8]. Thus, transverse polarization can be used as a probe of physics beyond the SM, when small amplitudes from new physics interfere with larger SM ones. Without the positron polarization, however, there is no visible effect.

3 Experimental issues

3.1 Polarimetry

The baseline NLC design includes a laser-backscattering Compton polarimeter to measure the electron beam polarization with an expected accuracy of 1% or better [9,10]. For the Giga-Z physics program, an accuracy of 0.25% should be achievable in an optimized setup, which is a factor two improvement over SLD's Compton polarimeter. Above the W-pair threshold, the SM asymmetry in forward W pairs can also be used [9]. Sub-1% polarimetry using this technique will require reduction of the background to the W-pair sample below 1%.

If the positron beam can also be polarized, significant improvements in polarimetry are possible. At Giga-Z, the polarimetry error can be improved to 0.1% using the 'Blondel scheme'. In this method, one measures the three independent asymmetries [11,12]:

$$
\begin{aligned}
A_1 &= \frac{N_{LL} - N_{RR}}{N_{LL} + N_{RR}} \\
A_2 &= \frac{N_{RR} - N_{LR}}{N_{RR} + N_{LR}} \\
A_3 &= \frac{N_{LR} - N_{RL}}{N_{LR} + N_{RL}} = \mathcal{P}_{\text{eff}} A_{LR},
\end{aligned}
\tag{12.5}
$$

where $\mathcal{P}_{\text{eff}}$ is given by Eq. (12.3). From these three measurements, one can determine A_{LR} (and hence the weak mixing angle) along with $\mathcal{P}_-$ and $\mathcal{P}_+$. It should be noted that $\mathcal{P}_{\text{eff}}$ is typically substantially higher than either $\mathcal{P}_-$ or $\mathcal{P}_+$ and has a smaller uncertainty. For example, if $\mathcal{P}_- = 80\%$ and $\mathcal{P}_+ = -60\%$, then $\mathcal{P}_{\text{eff}} = 94.6\%$, and the error on $\mathcal{P}_{\text{eff}}$ is proportional to the difference from 100%. With a Giga-Z sample using these polarization values, A_{LR} can be determined to an accuracy of 10^{-4} and the beam polarizations to an accuracy of 10^{-3}. These estimates are derived in Chapter 8, Section 1. An advantage of the Blondel scheme for polarimetry is that the luminosity-weighted polarization, P_e^{lum}, is directly measured. A Compton polarimeter measures the average beam polarization and small corrections may be needed to extract P_e^{lum}. It should be noted that a Compton polarimeter is still needed to measure the difference between the right-handed and left-handed beam polarizations. One also needs to understand the relative luminosities for the four beam polarization states (at the level 10^{-4} for Giga-Z).

Away from the Z-pole, the Blondel scheme with polarized positrons can also be applied to W-pair events. Using W pairs when both beams are polarized, an error on the beam polarizations of 0.1% should be achievable. The large W-pair physics asymmetry can be fit together with the beam polarizations, without sensitivity to backgrounds or assumptions about the polarization asymmetry in W interactions.

3.2 Frequency of spin flips

Depending on the method for producing polarized positrons, it may be difficult to achieve fast reversals of the positron helicity. For the polarized electron source, helicity reversals are easily done at the train frequency (120 Hz for NLC or 5 Hz for TESLA) using an electro-optic Pockels cell in the polarized source laser system. At SLC, the 120 Hz random helicity was very useful in controlling possible small left-right asymmetries in luminosity. Helicity reversals that are fast compared to any time constants for machine feedbacks are desirable. If fast helicity reversals are not possible, then relative integrated luminosities for the different polarization states need to be measured to better than 10^{-4} for Giga-Z. This should be achievable using forward detectors for Bhabha and radiative Bhabha events.

3.3 Run time strategy for LL, LR, RL, RR

One of the advantages of polarizing the positron beam is the increase in event rate by running in the (higher cross section) LR or RL polarization states. However, to take advantage of the Blondel technique for polarimetry and A_{LR} measurements, it is necessary also to accumulate data in the LL and RR states. However, it has been shown that only 10% of the running time has to be spent in the lower-event rate LL and RR states to achieve adequate statistics for the asymmetry measurements [13]. One anticipates equal run times for the LR and RL configurations, even though some physics analyses may benefit most from selecting one of these configurations for enhancing or suppressing W pairs or to enhance a cross section for a new process. Of course, some new physics searches will benefit from choosing those configurations that are suppressed in the SM.

4 Sources of polarized positrons

Several techniques have been suggested for producing polarized positrons for a linear collider. Present designs are largely conceptual, and much work remains before they can be realized.

In 1979, Mikhailichenko and Balakin [14] proposed generating circularly polarized photons by running a high-energy electron beam through a helical undulator. These photons are directed onto a thin target, where they produce e^+e^- pairs. Selecting positrons near the high-energy end of the spectrum gives a sample with appreciable polarization. Okugi *et al.* [15] have proposed generating polarized photons by colliding intense circularly polarized laser pulses with few-GeV electron beams. Variations on this theme have been proposed in an attempt to mitigate the rather extreme requirements on laser power by using an optical cavity to concentrate and store multiple laser pulses [16,17]. Finally, Potylitsin [18] has proposed directing a 50 MeV beam of polarized electrons onto a thin target.

4.1 Helical undulator

In the baseline TESLA design, unpolarized positrons are generated by photons produced when the full-energy electron beam is passed through a 100 m long wiggler prior to collision. The photon beam is directed to a thin, rotating target where e^+e^- pairs are produced, and the positrons are subsequently captured, accelerated, and damped. This novel approach reduces the power dissipated in the positron target to manageable levels and significantly reduces radiation in the target area.

Replacing the wiggler with a helical undulator would in principle allow polarized positrons to be produced. The magnetic field created by a helical undulator has two transverse components that vary sinusoidally down the length of the device, the vertical component shifted in phase by 90° from the horizontal. Such a field is created by two interleaved helical coils of the same handedness, driven by equal and opposite currents. Typical fields are of order 1 T; the period of the sinusoidal field variation is about 1 cm. The resulting electron trajectory for a 150 GeV beam is a helix whose axis coincides with that of the undulator; the radius of curvature is measured in nanometers! The undulator coils must be quite compact, with an internal radius of several millimeters and an outer radius of about 1 centimeter [19].

Efficient positron production requires photon energies of about 20 MeV, which in turn necessitates electron beam energies of approximately 150–200 GeV. The photons produced within $\theta \approx 1/\gamma$ have high average polarization. Collimators which are arranged to absorb the radiation at larger angles remove about 80% of the flux. To compensate this loss, the undulator length must be about 200 meters, somewhat longer than that of the wigglers used in the TESLA positron source. The undulator requires a very low-emittance electron beam, which probably prevents reuse of the electron beam after it has been used for high-energy collisions. It is possible that one could direct the primary high-energy electron beam through the undulator prior to collision. A drift space of about 200 meters between the undulator and the target is required to achieve the required photon beam size.

The highly polarized photons produced in the undulator are directed against a 0.4 X_0 target, where pair production can occur. Positrons produced with energies above

15 MeV are highly polarized. With this energy cut, roughly 0.025 e^+/incident photon is collected and 60% polarization is obtained [19]. Collection of the positrons requires solenoidal magnets, rf acceleration, and a predamping ring to handle the enlarged phase space. On paper, the scheme can generate the needed positron bunch currents.

The undulator scheme makes excellent use of the high-energy electron beam as the source of polarized photons. The low emittance requirements probably preclude the use of the post-collision beam. Whether the primary, pre-collision beam should be run through the undulator, or a dedicated beam should be generated for the sole purpose of positron production is a choice still being debated. A helical undulator generates positrons of a single helicity, so other means must be developed to flip the spin, and preferably to do so rapidly. Many of the photons could be absorbed in the undulator coil, so a workable design must accommodate many kilowatts of power dissipation.

4.2 Backscattered laser

A second method for producing highly polarized photons with enough energy to produce electron-positron pairs on a thin target involves backscattering an intense circularly polarized laser beam on a high-energy electron beam. The highest energy photons are strongly polarized and have helicity opposite to that of the incident laser light. As above, positrons are produced when these photons intercept a thin target. The highest-energy positrons are strongly polarized.

Omori and his collaborators have made a conceptual design of a laser-backscattering polarized positron source suitable for NLC/JLC [20]. They arrange for multiple collisions between polarized laser pulses from 50 CO_2 lasers and a high-current 5.8 GeV electron beam. The laser system must provide 250 kW of average optical power, which is regarded as extremely ambitious. Positron production is accomplished just as in the helical undulator scheme above. Simulations indicate that 9.4% of the incident photons produce a positron above 20 MeV, 26% of which are accepted into the pre-damping ring, with an average polarization of 60% [20].

This scheme makes production of polarized positrons independent of the high-energy electron beam, hence independent of its energy, but does so at the very considerable expense of a dedicated high-current linac and a very complex laser system. The estimated power required by those systems is roughly 10% of that required for the whole collider facility.

5 Conclusions

A polarized positron beam at a LC would be a powerful tool for enhancing signal-to-background, increasing the effective luminosity, improving asymmetry measurements with increased statistical precision and reduced systematic errors, and improving sensitivity to non-standard couplings. Suppression of W-pair backgrounds can be improved by a factor 3 with 60% positron polarization. By limiting the running time allotted for LL and RR modes to 10%, the effective luminosity for annihilation processes can be enhanced by 50%. For asymmetry measurements, the effective polarization is substantially increased (*e.g.*, from 80% to 95%) and the systematic precision is improved by a factor 3. With these features, a polarized positron beam may provide critical information for clarifying the interpretation of new physics signals. Polarized positrons are needed to realize the full potential for precision measurements, especially those anticipated for Giga-Z running at the Z-pole.

Designs of polarized positron sources have not reached maturity. Several approaches have been proposed, the most promising of which uses a helical undulator, but to date no real engineering designs, cost estimates, or experimental proofs of principle are available. Since much of the benefit of a polarized positron source would be negated if luminosity were compromised, it is very important that eventual designs have some margin on projected yields. Also, the source needs to be available for all collision energies. The helicity of a polarized positron source may be difficult to switch quickly and provision needs to be made to allow this, with a strong motivation to have helicity-switching capability at the train frequency. Present designs must be further developed and additional R&D is needed to pursue new schemes, some of which have been mentioned here.

Though a polarized positron source is not yet advanced enough to be included as part of the baseline linear collider design, it is an attractive feature that should be pursued as an upgrade. Site layout and engineering for a linear collider baseline design should accommodate such an upgrade at a later date. This has been done for the TESLA design and needs to be done for the NLC design as well.

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