

# Status of Linear Collider Beam Instrumentation Design

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## Abstract

This note describes the current status of a design for measuring beam parameters at a future  $e^+e^-$  linear collider to an adequate precision for the foreseen physics program. The physics requirements for understanding the beam polarization, beam energy, total luminosity, and luminosity spectrum are reviewed. A strategy to reach the required precision is outlined which includes both beam-based instrumentation and analyses of physics processes at the interaction point. Further work required to establish a baseline design is also discussed.

This note describes work performed in the framework of the American Linear Collider Physics Group<sup>1</sup> by the IP Beam Instrumentation working group<sup>2</sup>.

## 1 Introduction

The distinct advantage of a high-energy  $e^+e^-$  linear collider (LC) for making precision measurements is the well defined initial state in the collision process. This advantage can only be realized, however, if there is adequate instrumentation available to measure the beam properties at the interaction point (IP). In this note, a strawman design is outlined for measuring the beam polarization, beam energy, total luminosity, and luminosity spectrum to a precision which is adequate for the foreseen physics program.

To ensure the reliability of these measurements, this design uses a mixture of beam-based instrumentation and analyses of physics processes observed in the main detector. The inclusion of physics analyses in this strategy is important both as a cross check of the dedicated beam instrumentation, but also to verify that the beam

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<sup>1</sup><http://blueox.uoregon.edu/~jimbrau/LC/ALCPG/>

<sup>2</sup><http://www.slac.stanford.edu/xorg/lcd/ipbi/>

parameters have been extracted with the proper luminosity weighting at the collision point.

To make this discussion concrete, the NLC accelerator design has been chosen as a baseline. While some of the specific details differ between the various accelerator designs, most of the general issues described in this note are universally applicable to any high energy  $e^+e^-$  linear collider. While this design is by no means complete, the intent of this note is to document the direction of the current design work and identify areas which need more thought. To limit the scope of this note, the discussion is focused on the initial goal of an LC operating from  $t\bar{t}$  threshold to a collision energy near 1 TeV. Additional issues related to precision electroweak measurements near the Z-pole will also be mentioned where appropriate.

## 2 Polarization

A polarized electron beam was an essential feature of the SLD physics program at the SLC, allowing many precise measurements of parity-violating asymmetries. SLD made the world's most precise measurement of the weak mixing angle and provided key data for predictions of the Higgs mass[1]. Similarly, polarization is expected to play a key role at a future LC for interpreting new physics signals and for making precision measurements[2, 3]. The baseline designs for the NLC/JLC and TESLA machines provide for polarized electron beams with  $\mathcal{P}_{e^-} \approx 80-90\%$  expected. Initially the positron beams will be unpolarized, although there is significant interest and physics motivation for realizing polarized positron beams in future upgrades.

### 2.1 Physics Requirements

There are three main classes of analyses which benefit from polarization information. First, direct measurements of parity-violating asymmetries require beam polarization measurements at a precision comparable to the expected statistical uncertainty for each channel. Second, the understanding of new physics signals can be elucidated by the manipulation of helicity states in the production process. Third, for any rare process with significant background from W-pair production, the manipulation of helicity states can effectively be used to 'turn off' this background source.

For most of the physics analyses at the LC which utilize beam polarization, accuracy in the polarization determination of 1% should suffice due to the small cross sections involved. Precise measurements of Standard Model asymmetries, particularly in hadronic final states, will require a polarization determination to 0.5% or better[4, 5]. High statistics Giga-Z running at the Z-pole would benefit from polarimetry at the 0.1% level[6].

### 2.2 Luminosity-Weighted Polarization

A beam polarimeter, whether before or after the IP, measures the average beam polarization at its location. Due to effects from polarization spread, spin transport

between the polarimeter and the IP, and disruption and radiation from the beam-beam collision process, the polarimeter measurement result ( $\mathcal{P}^{\text{polarimeter}}$ ) can differ from the luminosity-weighted beam polarization ( $\mathcal{P}^{\text{lum-wt}}$ ). At the NLC, the largest source of polarization spread before the IP is expected to result from the 180-degree turnaround after the pre-Linac, where the beam energy is 8 GeV. The 0.25% energy spread there results in a spin diffusion of 1% rms. The polarization spread for different bunches along the bunch train is expected to be small, but should be measured. The polarization spread will have some correlation with the energy,  $E$ , and  $z$  of the particle distributions at the IP. Because the luminosity may depend on  $E$  and  $z$ , this can lead to  $\Delta\mathcal{P} = \mathcal{P}^{\text{polarimeter}} - \mathcal{P}^{\text{lum-wt}}$  being non-zero. Spin precession and spin diffusion from the final focus magnets are additional sources of  $\Delta\mathcal{P}$  that need to be considered. Also, the detector solenoid and the crossing angle result in a transverse B-field component that causes a small amount of spin precession. Beam-beam effects contribute to  $\Delta\mathcal{P}$  due to the disruption and deflection angles and due to spin-flip beamstrahlung radiation[7, 8].

Polarimetry downstream of the IP, if feasible, can provide direct measurements for some of the contributions to  $\Delta\mathcal{P}$ . Asymmetry measurements of some physics processes in the main detector may be useful for polarimetry and are advantageous because they directly measure  $\mathcal{P}^{\text{lum-wt}}$ . These measurements are slow, however, and do not provide a real-time diagnostic. They may also have significant backgrounds that complicate using them for polarimetry. Ideally, physics asymmetry measurements can be used together with beam-based polarimetry to confirm the estimated precision of each technique.

### 2.3 Compton Polarimetry

The primary polarimeter measurement will be performed by a Compton polarimeter located in the extraction line approximately 60 meters downstream from the IP[9]. An accuracy of  $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 0.25\%$  should be achievable[5]. This location in the extraction line is shown in Figure 1. It is at a secondary focus in the middle of a chicane with 20 mm dispersion, but with no net bend angle with respect to the primary IP. This extraction line geometry is feasible in the NLC design due to the non-zero crossing angle at the IP; beam losses in the extraction line are acceptable, both for machine protection[10, 11] and for detector backgrounds. (At TESLA the zero crossing angle at the IP severely limits the extraction line design and prevents the implementation of a polarimeter there.<sup>3</sup> Instead, a polarimeter located 630 meters upstream of the IP is currently being considered[12].) A location downstream of the IP is chosen so that beam-beam depolarization effects[7, 8] can be measured directly by comparing beams in and out of collision. Also, spin precession effects due to the final focus optics and beam-beam deflections can be studied by correlating the polarization and IP BPM measurements.

Compton polarimetry is chosen as the primary polarimetry technique for several reasons:

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<sup>3</sup>The TESLA IP design is currently under review and a crossing angle may be adopted anyways.

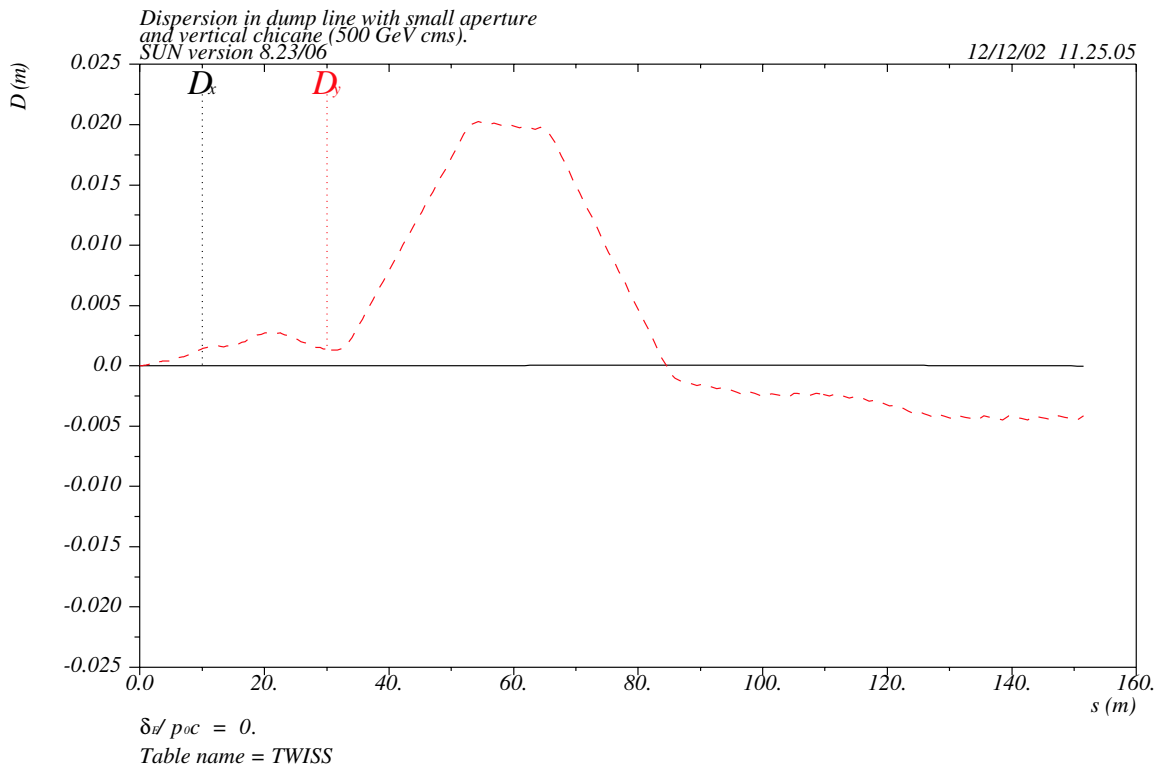
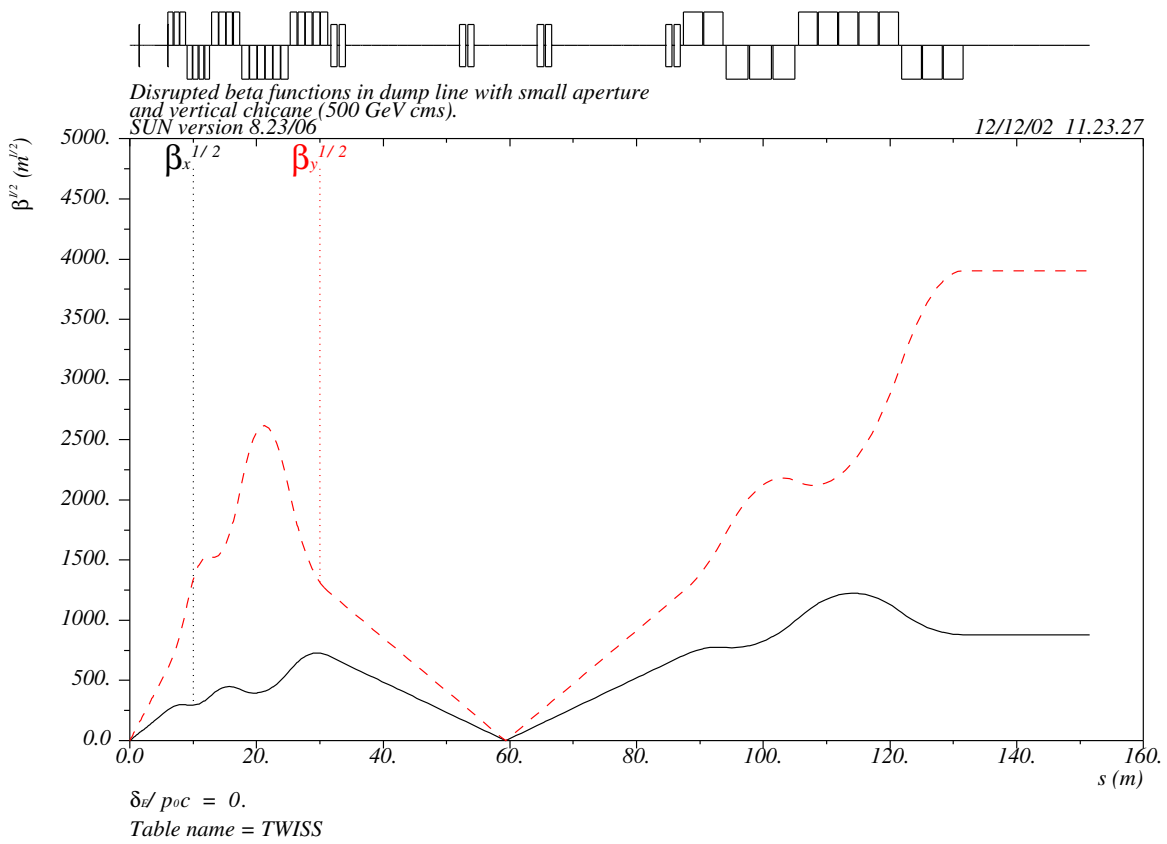


Figure 1: Beta-functions and dispersion in the extraction line as a function of distance from the IP. The Compton IP will be located at the secondary focus 60 meters downstream.

- the physics of the scattering process is well understood QED, with radiative corrections less than 0.1%[13];
- detector backgrounds are easy to measure and correct for by using 'laser off' pulses;
- polarimetry data can be taken parasitic to physics data;
- the Compton scattering rate is high and small statistical errors can be achieved in a short amount of time (sub-1% precision in a few minutes is feasible);
- the laser helicity can be selected on a pulse-by-pulse basis;
- the laser polarization is readily determined with 0.1% accuracy.

An Nd:YAG laser can be chosen with a wavelength of 1064 nm (1.165 eV). With this laser, the kinematic endpoint for Compton electrons scattered from a 250 GeV beam occurs at 45.8 GeV with an analyzing power of 93.5%. Figure 2 shows the resulting  $J=3/2$  and  $J=1/2$  Compton cross sections. A segmented electron detector sampling the flux of scattered electrons near the kinematic endpoint will provide a good polarization measurement with high analyzing power. The analyzing power for a power asymmetry measurement by an integrating Compton photon detector is much lower at 5.2%. Detectors to measure both the scattered electrons and photons, similar to those employed in the SLD Compton polarimeter,[14, 15] will be considered. A photon detector will interfere with the large beam stayclear needed in this region to accommodate the beamstrahlung photons. An invasive measurement with an insertable photon detector and the beams out of collision can be useful, however, as a systematic cross check of the polarization scale. Ideally, detectors should allow for measurements of both backscattered electrons and photons, and possibly to compare single and multi-Compton counting. These independent techniques can be extremely useful for evaluating systematic errors.

## 2.4 Polarimetry with both beams polarized

If the positron beam can be polarized along with the electron beam, or the machine is operated in  $e^-e^-$  mode, improved polarimetry becomes possible[4, 6, 16, 17]. First, for most asymmetry analyses an effective polarization given by  $\mathcal{P}_{\text{eff}} = \frac{\mathcal{P}_{e^-} + \mathcal{P}_{e^+}}{1 + \mathcal{P}_{e^-}\mathcal{P}_{e^+}}$  becomes the relevant figure of merit. For example, with  $\{\mathcal{P}_{e^+}, \mathcal{P}_{e^-}\} = \{80\%, 60\%\}$  one obtains  $\mathcal{P}_{\text{eff}} = 94.6\%$ . Compton polarimeter measurements with 0.25% accuracy per beam will yield a 0.1% accuracy on  $\mathcal{P}_{\text{eff}}$ , even with pessimistic assumptions on the correlations between the two polarimeters. Secondly, if an asymmetry analysis is being made on a mode with high statistics (particularly for Giga-Z operations), then the luminosity-weighted average beam polarizations can be extracted directly from the data using the Blondel technique[17]. The Blondel scheme does not, however, eliminate the need for precise polarimeters as the polarization asymmetry  $\Delta^+ = \mathcal{P}_{e^+}^L - \mathcal{P}_{e^+}^R$  for each beam must be independently measured. The systematics associated with the measurement

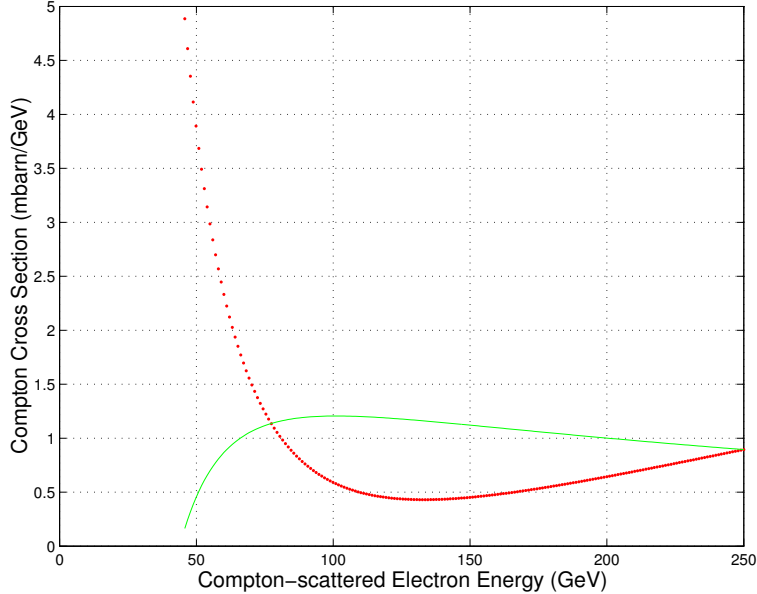


Figure 2: *Compton cross section for scattering of 1064 nm photons with a 250-GeV electron beam. The  $J=3/2$  ( $1/2$ ) cross section for electron and photon spins aligned (anti-aligned) is shown in dotted red (solid green).*

of  $\Delta^+$  will depend on the frequency with which the helicity of the positron beam can be reversed, and may limit the accuracy on  $\mathcal{P}_{\text{eff}}$ .

For NLC operations with  $e^-e^-$  collisions, both beams will be highly polarized. In this case, a similar  $\mathcal{P}_{\text{eff}}$  can be defined and asymmetries in t-channel Møller scattering can be used to determine the luminosity-weighted beam polarizations. The statistics are not as high as for Giga-Z, but can still be adequate especially if there is good detector coverage at small polar angles. With sufficient luminosity, the beam polarization can be determined to 0.5% or better using this method[18].

## 2.5 Polarimetry with W-pairs

Beam polarization measurements are also possible using the Standard Model asymmetry for t-channel W-pair events, even if only the electron beam is polarized[4, 19]. By performing a complete analysis of the rate asymmetry as a function of  $W^-$  scattering angle, the beam polarization can be extracted from the t-channel amplitude while simultaneously fitting for anomalous triple-gauge couplings (TGCs) in the s-channel amplitude. The statistical precision of this technique appears quite good if high efficiency forward tracking is available. A limiting systematic of this technique is the uncertainty on the background in the W-pair selection. The relative background uncertainty translates into an equivalent uncertainty on the extracted polarization, so for example a 0.5% uncertainty on the background level will limit the understanding of  $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-}$  to 0.5%. If both beams are polarized this background fraction can be extracted directly from the data by taking a small amount of luminosity (10%) in the

'wrong' helicity beam configurations.

### 3 Beam Energy

Precise knowledge of the collision energy  $\sqrt{s}$  has always been a tremendous advantage of  $e^+e^-$  colliders for doing precision measurements, particularly of particle masses. At LEP, for example, the precision energy determination using resonant depolarization allowed an exquisite measurement of the Z boson mass to a precision of 2 MeV or 23 ppm. Life will not be nearly as easy at a future linear collider, however, as the resonant depolarization technique used in storage rings cannot be applied. The precision necessary for the energy range  $2M_t < \sqrt{s} < 1\text{TeV}$  is much more modest than the LEP energy scale, and a relative precision of  $1 \cdot 10^{-4}$  or 100 ppm appears to be adequate. As outlined below, this level of precision is the goal for beam-based spectrometers of two different designs, potentially using the Z-pole resonance as a cross check. Physics analyses using radiative return events  $e^+e^- \rightarrow Z^0\gamma$  or W-pair production can also be used to cross check these measurements of the beam energy.

#### 3.1 Physics Requirements

There are two main types of physics analyses which depend upon precise knowledge of the collision energy  $\sqrt{s}$ . The first is a scan of the production threshold lineshape which is sensitive to a particles mass. The second is direct reconstruction of a particle resonance in the continuum where constrained kinematic fits may be used to improve the mass resolution. In both cases, the relative uncertainty on  $E_{\text{beam}}$  translates directly into an overall scale error on the extracted particle mass.

The canonical example of a lineshape scan is a measurement of  $M_t$  by scanning the  $t\bar{t}$  threshold at  $\sqrt{s} \sim 350$  GeV. A relative precision on  $E_{\text{beam}}$  of  $2 \times 10^{-4}$  or 200 ppm would give a 35 MeV uncertainty on  $M_t$  which is below the statistical precision of 40 MeV expected in  $10 \text{ fb}^{-1}$ , and is also probably well below the limiting theoretical uncertainty expected for this method[20].

An example of a continuum measurement is the determination of  $M_H$  by direct reconstruction of the Higgstrahlung process. Using an analysis similar to the W mass measurement at LEP II, it is expected that a total experimental uncertainty of 50 MeV can be achieved[21]. While the additional scale uncertainty coming from the knowledge of the beam energy depends on the exact value of  $M_H$  and the collision energy at which the data is taken, for a light higgs the uncertainty is approximately given as  $\delta M_H/M_H \approx \delta E_{\text{beam}}/E_{\text{beam}}$ . A 200 ppm uncertainty on  $E_{\text{beam}}$  then leads to a 30 MeV uncertainty on a 150 GeV Higgs boson.

For high energy running ( $2M_t < \sqrt{s} < 1\text{TeV}$ ), a relative precision on  $E_{\text{beam}}$  of 100-200 ppm appears to be adequate. For analyses proposed at lower energy to measure the electroweak parameters  $\sin^2\theta_W^{\text{eff}}$  and  $M_W$ , the requirements on the beam energy precision are significantly tighter. Measuring  $M_W$  by means of a threshold scan is only interesting if the total error can be reduced to around 5 MeV, which requires an equivalent precision of better than 50 ppm on  $E_{\text{beam}}$ . For measurements

Table 1: Beam energy requirements for  $\sin^2\theta_W^{\text{eff}}$  measurements

	$\Delta \sin^2\theta_W^{\text{eff}}$	$\Delta E_{\text{beam}}$ [MeV]	$\Delta E_{\text{beam}}$ [ppm]
SLD final	0.00027	15	320
$\mathcal{P}_{e^-} = 80\%$ only	0.00005	5	110
$(\mathcal{P}_{e^-}/\mathcal{P}_{e^+}) = (80/50)\%$	0.00002	2	45

of  $\sin^2\theta_W^{\text{eff}}$  from  $A_{\text{LR}}$ , precise knowledge of  $E_{\text{beam}}$  is required to correct the measured value back to the theoretically useful  $Z^0$  pole value. The precision required depends upon the ultimate experimental precision attainable on the weak mixing angle[5]. Table 1 shows the final SLD result[1], along with the ultimate experimental limit from the beam polarization uncertainty for polarized electrons only ( $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 0.25\%$ ) and both beams polarized ( $\Delta\mathcal{P}_{\text{eff}}/\mathcal{P}_{\text{eff}} = 0.10\%$ ). For these two scenarios, the beam energy uncertainty which would contribute an additional uncertainty equal to half of this polarization uncertainty on  $\Delta \sin^2\theta_W^{\text{eff}}$  is indicated.<sup>4</sup> If the Blondel scheme can be realized with  $\mathcal{P}_{e^-} = 80\%$  and  $\mathcal{P}_{e^+} = 50\%$ , for example, the beam energy must be known to about 2 MeV (40 ppm) to avoid becoming the limiting uncertainty on determining  $\sin^2\theta_W^{\text{eff}}$ .

It should be stressed that the requirements on  $\Delta E_{\text{beam}}$  listed above are realistic targets which are *required* to carry out the physics program at a high energy  $e^+e^-$  collider. More precise measurements of  $E_{\text{beam}}$  are, of course, always a good thing, but the actual physics impact of any improvement is not clearly apparent without more detailed studies of particular analyses. One could certainly imagine a scenario where weakly interacting quasi-stable particles are pair produced, and a threshold scan with high luminosity could potentially measure the mass of this particle to better than 100 ppm.

### 3.2 Spectrometers

The deflection of a charged particle traversing a magnetic field is a well established method for measuring a particle's momentum. In the strawman design, it is proposed to build two independent spectrometers each capable of 100 ppm accuracy to allow a direct cross check of the energy scale. The first is a BPM-based spectrometer located upstream of the primary IP using a chicane layout and RF BPMs. The second is a SLC-style WISRD spectrometer located in the extraction line.

An inline BPM spectrometer using button BPMs was successfully operated at LEP II to cross check the energy scale for the W mass measurement to a precision of 200 ppm[22]. At a future LC, this device would use RF BPMs which can potentially achieve precisions on the transverse beam position approaching 10 nm[23]. Located upstream of the primary IP, concerns about emittance dilution restrict the possible spectrometer bend angle to something less than 100 microradians. A chicane design as shown in Figure 3 is foreseen to alleviate the need for a bend in the LC layout and to allow beam-based alignment and linearity measurements of the spectrometer

<sup>4</sup>It has been assumed that the beam energy uncertainties are correlated:  $\Delta\sqrt{s} = 2\Delta E_{\text{beam}}$ .

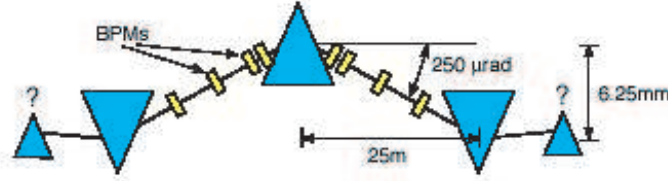


Figure 3: A schematic outline of an accelerator dipole chicane which could accommodate a BPM-based magnetic spectrometer[24].

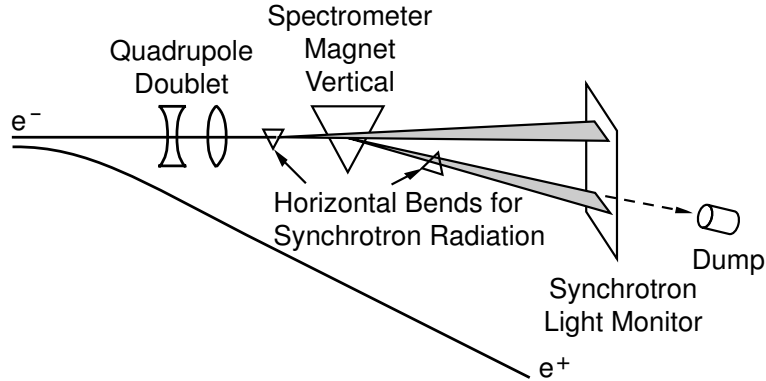


Figure 4: The SLC WISR D beam energy spectrometer.

BPMs. RF BPMs capable of 10 nm precision and stability would be able to make a 100 ppm measurement of  $E_{\text{beam}}$  with a lever arm on the order of meters, although significant technical challenges to a spectrometer of this design remain.

At the SLC, the WISR D spectrometer was successfully used to make beam energy measurements at 120 Hz with a precision of 250 ppm at  $E_{\text{beam}} = 45$  GeV[25]. As shown in Figure 4, the WISR D consists of a strong vertical analyzing dipole flanked by two weaker horizontal dipole magnets. The synchrotron radiation stripes produced by these two weaker dipoles are detected downstream on wire arrays, such that the deflection angle of the beam in the analyzing magnet can be directly monitored. The beam energy is then calculated as  $E_{\text{beam}} = l/x \int B \cdot dl$ , where  $l$  is the distance from the analyzing magnet to the wire screen,  $x$  is the separation between the synchrotron stripes, and  $\int Bdl$  is the integrated bending field of the analysis magnet.

The systematic uncertainties of the SLC WISR D are dominated by the alignment tolerances of magnets, particularly the relative rotations between the stripe producing dipoles, which contribute 170 ppm to the total error. The WISR D, with some modifications, may be able to meet the 100 ppm goal for the LC if care is taken to design the system into the machine at an early stage[26]. It provides many benefits, including the possibility of bunch-by-bunch measurements, in a simple passive device which can be operated with essentially 100% duty factor. To improve the precision of the device, improvements can be made in the magnetic field survey, the synchrotron radiation detector design, and the overall geometry of the device. The location of the WISR D in the extraction line also allows the possibility to directly measure the

energy distribution of the disrupted beam which could be used as a real-time monitor of the luminosity spectrum.

One serious drawback for spectrometer measurements is the difference between  $E_{\text{beam}}$  at the spectrometer and the luminosity-weighted beam energy producing physics events at the primary IP. This is a universal problem for any method of measuring the beam energy using beam-based instrumentation which contributes an additional uncertainty to the method. In the end, it may well limit the achievable precision on the luminosity-weighted beam energy, but without a precise measure of the beam energy somewhere to start with, it becomes a moot point.

### 3.3 Radiative Returns

The kinematics of  $e^+e^- \rightarrow f\bar{f}\gamma$  radiative return events observed in the main detector potentially can be used to reconstruct the luminosity-weighted collision energy to the desired precision. In the most likely tree-level process, a single photon is emitted collinear to the incoming particles, and the invariant mass of the  $f\bar{f}$  system can be reconstructed assuming a three-body final state as

$$\frac{s'}{s} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin(\theta_1 + \theta_2)|}{\sin\theta_1 + \sin\theta_2 + |\sin(\theta_1 + \theta_2)|}, \quad (1)$$

where  $\theta_1$  and  $\theta_2$  are the azimuthal scattering angles of the two outgoing fermions. Due to the strong resonance of the  $Z^0$  pole, there will be a peak in the  $\sqrt{s'}$  spectrum which could in principle be used to measure the  $Z^0$  mass as shown in Figure 5[27]. Since  $M_Z$  is well known from measurements at LEP, this analysis can be turned around to determine the collision energy  $\sqrt{s}$  using the observed peak position and the known value of  $M_Z$  as inputs. This analysis is currently being performed by the LEP collaborations, and more details can be found, for example, here[28].

The  $q\bar{q}\gamma$  final state has the best statistical sensitivity, but uncertainties in the hadronization process probably limit the precision in this channel to  $\sim 50$  MeV. This problem is avoided in the  $\mu^+\mu^-\gamma$  final state, although the requirements for the tracking detector are rather stringent. To obtain a 100 ppm uncertainty on  $E_{\text{beam}}$  requires an absolute  $\theta$  measurement of the muon tracks in the forward direction ( $\theta \approx 200\text{mRad}$ ) with an accuracy approaching 100 ppm. A forward detector made from planes of silicon strips or pixels has been proposed to achieve the performance necessary for both the radiative return and the  $d\mathcal{L}/dE$  analysis described in Section 5. An example detector design for the NLC large detector is shown in Figure 6.

One distinct advantage of this method is that it allows a direct measurement of the luminosity-weighted beam energy at the interaction point, and at the W-pair threshold it can potentially be pushed to provide an absolute measurement of  $E_{\text{beam}}$  at the level of 5 MeV. Complications due to the beam energy spread, large disruption angles at the IP, and correlations between the luminosity spectrum and the collision energy may ultimately limit the achievable precision of this technique.

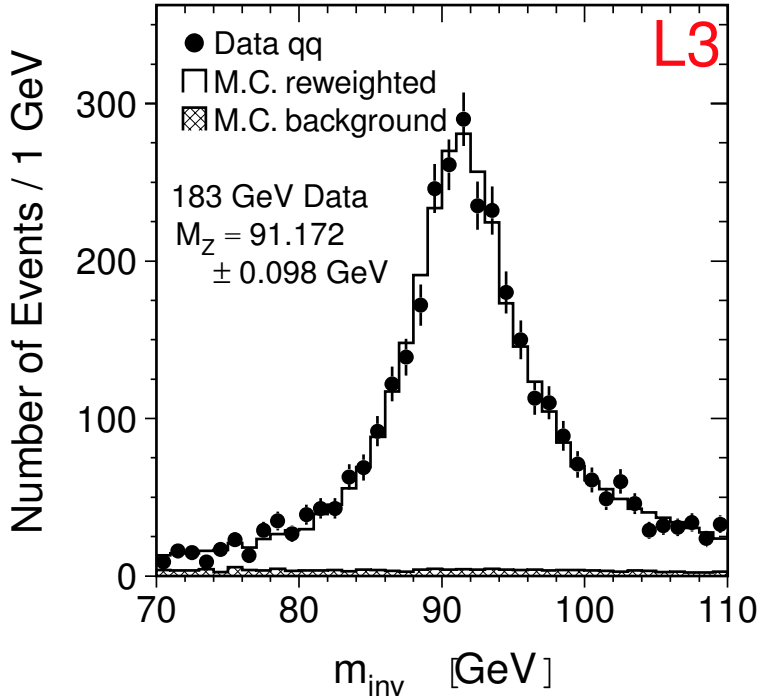


Figure 5: Radiative return analysis by the L3 collaboration.

### 3.4 Energy Width

In addition to measuring the absolute energy scale, there is a strong need to make measurements of the energy width of the incoming beams. Unlike in a storage ring, at a linear collider the incoming energy spectrum ( $dn/dE$ ) is very non-Gaussian and highly dynamic, particularly in the NLC design where the RMS energy width of the beam is expected to be around 0.3%. While this is correlated to the extraction of the luminosity spectrum discussed in Section 5, reasonable knowledge of the energy distribution itself is probably a necessary component of any  $d\mathcal{L}/dE$  analysis.

It is presumed that there will be some diagnostic monitor near the end of the linac which can make measurements of the RMS width and  $dn/dE$  population with reasonable precision. There is some hope that the extraction line WISR spectrometer can also give some width information by looking at the synchrotron stripe distribution with the beams out of collision. At this time, it is not known whether one or both of these instruments would be adequate for measuring the energy width, and further work to specify the exact requirements is needed.

## 4 Luminosity

One of the many successes of the LEP program was the understanding of the absolute luminosity scale to a relative accuracy of 0.07% which allowed exquisite measurements of the  $Z^0$  lineshape[29]. Achieving this level of precision, however, is no mean feat and it should not be assumed that similar measurements will be available, nor are they

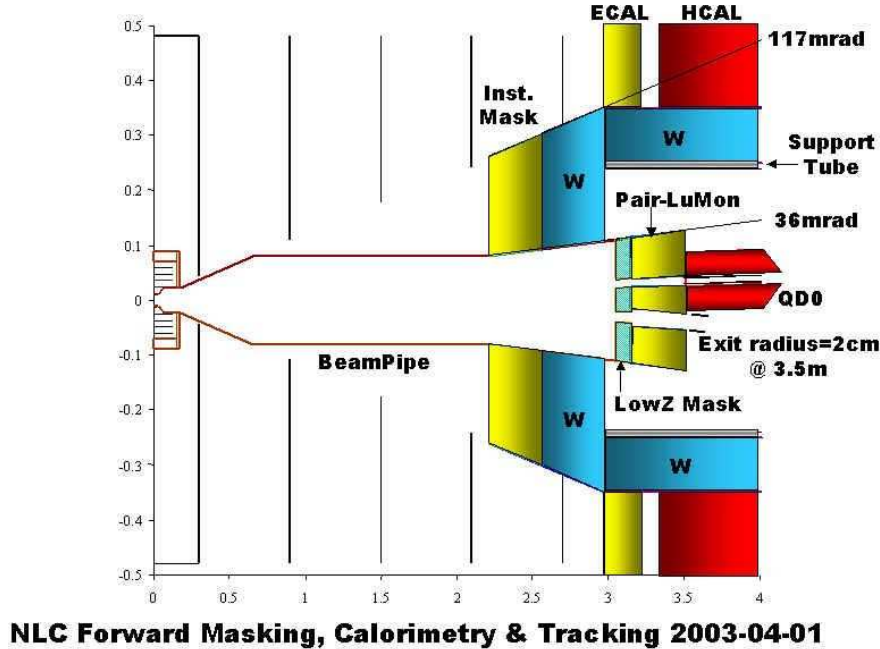


Figure 6: Forward detector layout in the NLC large detector. Scale is in meters.

warranted, for LC physics.

## 4.1 Physics Requirements

The most pressing need for precise measurements of absolute luminosity come from measurements of SM cross sections at high energy as a test of contact interactions and other indirect probes of new physics arising at a higher mass scale. For example, the total hadronic cross section at 500 GeV is approximately 2 pb. With a yearly luminosity of around  $200 \text{ fb}^{-1}$  and high selection efficiency, one can expect to measure the total hadronic cross section to a relative statistical precision of around 0.2% *per year*. Other experimental uncertainties may limit the ultimate precision which can be obtained, but there is clearly a physics need to determine  $\delta\mathcal{L}/\mathcal{L}$  to a few tenths of a percent.

Other analyses which require absolute luminosity information are far less stringent. The measurements of the relative Higgs branching fractions, for example, are limited to a relative precision of 1% due to the relatively low rate of Higgs production, and even analyses comparing the Higgs branching fractions to the Higgs total width do not need measurements of  $\delta\mathcal{L}/\mathcal{L}$  better than 1%.

It is worth noting that there is also a need for precise *relative* luminosity measurements, particularly for calibration runs at the  $Z^0$ -pole. One useful technique for performing a cross check of beam-based spectrometers is to scan the  $Z^0$  resonance and compare with the known  $Z^0$  mass. This technique was used during the 1998 SLD run to determine the absolute  $\sqrt{s}$  scale of the SLC to an accuracy of 29 MeV[30].

To achieve a relative precision of 50 ppm on  $E_{\text{beam}}$ , one must be able to determine

$M_Z$  from a lineshape scan to the level of 5 MeV. An analysis of this sort will require about  $8 \text{ pb}^{-1}$  total delivered in a three point  $Z^0$  scan, and knowledge of the relative luminosity delivered at each scan point to the level of 0.03%. Achieving relative precision is significantly easier than absolute precision, so it is not foreseen that this relative luminosity requirement will be a significant problem. More of a problem may well be the knowledge of the beam energy width during the scan, as this width must be convoluted with the  $Z^0$  lineshape to accurately predict the expected event rate. A detailed example of this sort of analysis would be most welcome.

## 4.2 Instrumentation

Traditionally, measurements of absolute luminosity at  $e^+e^-$  colliders have been made using far-forward Bhabha scattering observed in compact calorimeters. A similar technique is foreseen at a high-energy LC, although the rather hostile forward environment and constraints from necessary mechanical elements may lead to a slightly different final design. Currently, it is planned to install a segmented calorimeter which will subtend the angular range from roughly 40 - 120 mRad. This detector is shown as the instrumented mask in Figure 6. The primary purpose of this detector is to monitor forward Bhabha scattering to provide the absolute luminosity scale[31]. While a SiW sandwich design is probably the leading candidate for this detector, other possibilities are being pursued and it is not at all clear what is really the best choice.

In addition to the luminosity monitor, it is envisioned to put a second device at much smaller angles, subtending the range from 5 - 40 mRad. The purpose of this device is primarily to act as a real-time monitor of instantaneous luminosity by detecting the large quantity of soft  $e^+e^-$  pairs produced in the collision process[32, 33]. In addition, there is a pressing physics need for this device to be able to identify single high energy electrons ( $\simeq 200\text{GeV}$ ) to veto two-photon backgrounds from expected SUSY production channels[34]. This detector is shown as the pair monitor in Figure 6. See below for further discussion of the utility of this device.

## 5 Luminosity Spectrum

While measurements of beam polarization and beam energy have been made at previous  $e^+e^-$  colliders, a new feature of the high energy LC environment is the presence of very strong beam-beam interactions which produce a large quantity of ‘beamstrahlung’ photons before the hard scattering process. At the SLC, for example, about 0.1% of the incoming beam energy was lost to beamstrahlung photons, while for the baseline NLC-500 design this loss is several percent per beam. While the magnitude of this energy loss is rather comparable to initial state radiation, unlike ISR this process depends critically on the geometry and alignment of the incoming beams which are not known *a priori* and may change with beam conditions. While the effects of ISR can be predicted to very high accuracy by applying QED, the effects of beamstrahlung really must be directly measured.

## 5.1 Physics Requirements

A prediction of the luminosity spectrum expected at a 500 GeV linear collider of the NLC design is shown in Figure 7. For many physics analyses foreseen at a future LC, the knowledge of the luminosity spectrum ( $dL/dE$ ) arising from this beamstrahlung process is critically important. It is worth noting that the entire spectrum must be understood, both the long tail (dominated by ISR and beamstrahlung effects) and the core shape (dominated by the energy spread at the end of the linac).

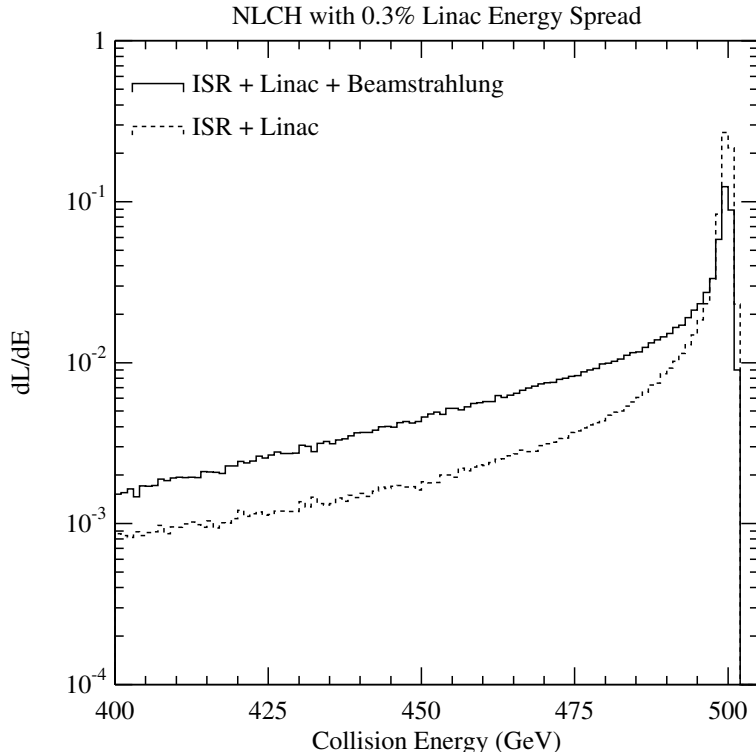


Figure 7: *NLC luminosity spectrum including the effects of initial state radiation, beamstrahlung, and linac energy spread.*

There are two main classes of analyses to consider. First, any threshold or peak scans to extract particle masses or couplings is sensitive to the shape of this luminosity spectrum since the observed rate is the convolution of the true lineshape with this  $d\mathcal{L}/dE$  curve. Second, any analysis using direct reconstruction is sensitive due to the mass bias arising from the shift of the mean effective collision energy away from twice the incoming beam energy.

An example of the threshold scan dependence comes from the measurement of the top quark mass at  $t\bar{t}$  threshold. Previous studies have shown that the population in the tail of the luminosity spectrum must be understood at the 1% level and the width of the core distribution had to be known to 0.1% of the beam energy to keep the systematic uncertainty on the top quark mass from this source below an acceptable level of 50 MeV[35, 36, 37]. These studies found little sensitivity to the details of the

core shape, but see below for further discussions of this effect.

A mass bias analysis for slepton reconstruction has been done for CLIC[38] and it draws similar conclusions about the tail of the  $d\mathcal{L}/dE$  distributions. The amount of luminosity in the tail has to be known to 1% or it begins to dominate the uncertainty on the extracted slepton mass. There is little sensitivity to energy spread or core shape.

Many other physics analyses at an LC are likely to be effected by uncertainties in the  $d\mathcal{L}/dE$ . A comprehensive survey of the effects remains to be done.

## 5.2 Bhabha Acolinearity

The primary method envisioned to measure the luminosity spectrum is to consider the acolinearity of Bhabha events produced at the IP.[39, 40, 41, 36] With the assumption that single colinear photon emission is dominant, the invariant mass of the outgoing  $e^+e^-$  pair ( $\sqrt{s'}$ ) can be reconstructed using the same kinematic relation as the radiative return analysis described in Section 3. In the small angle approximation relevant for acolinearity in Bhabha scattering, this can be simplified as

$$\sqrt{\frac{s'}{s}} \approx 1 - \frac{\Delta\theta}{2 \sin \theta}, \quad (2)$$

where  $\theta$  is the mean Bhabha scattering angle and  $\Delta\theta$  is the acolinearity angle. The effect of multiple photon emission including correlations in the beamstrahlung rate between the two incoming particles is one of many complicating factors that need further study.

The uncertainty on reconstructing the effective collision energy in this manner is approximately given as  $\sigma_{\sqrt{s'}} \approx \sigma_{\Delta\theta} E_{\text{beam}} / \sin \theta$ . Because of the  $\sin \theta$  term in the denominator, the most sensitive range of Bhabha scattering for this analysis is around 200 mRad, even though the rate is much higher at more forward angles. For this reason, the same forward tracker which is necessary for measuring  $E_{\text{beam}}$  with radiative returns is also critical for extracting the  $d\mathcal{L}/dE$  spectrum with Bhabha events.

There are significant complications to extracting the full  $d\mathcal{L}/dE$  spectrum from simply considering the acolinearity angle alone. First, when relaxing the assumption of single acolinear photon emission, the acolinearity angle is actually sensitive to the boost of the system, and does not directly measure  $\sqrt{s'}$ . Second, due to the dynamics of the colliding bunches, the emission of beamstrahlung photons is correlated between the two incoming bunches requiring an accurate understanding of the details of the collision process. Third, the incoming beams have a natural spread in energy with a complex shape due to the linac which also may not be known *a priori*, but must be properly accounted for to extract the  $d\mathcal{L}/dE$  spectrum. A complex shape for the energy spread makes it very difficult to extract and cross check the resolution on  $d\mathcal{L}/dE$  from the data. Fourth there are correlations among all the beam parameters (positions, angles, and energy) caused by dispersion, chromatic aberrations, and others that complicate the extraction of the  $d\mathcal{L}/dE$  spectrum by any method.

Several studies have shown that the statistical precision in the forward Bhabha events is more than adequate to extract the  $d\mathcal{L}/dE$  spectrum[36, 42, 43]. These

studies have also touched upon some of the problems with this method mentioned above, although more work here is needed. In particular, more emphasis needs to be placed on the systematic uncertainties, necessary external inputs, the effects of asymmetric beams, and understanding of beam-beam correlations in extracting the true luminosity spectrum.

To properly extract the  $d\mathcal{L}/dE$  spectrum it is likely that additional information beyond the acolinearity angle will be necessary. Measuring the outgoing fermion energies to sufficient precision using a forward calorimeter may help considerably, although a complete study to investigate this possibility remains to be done.

### 5.3 Other Instrumentation

While measuring beam properties directly will never provide a precise measurement of the luminosity spectrum (any more than it can provide a precise measurement of the delivered luminosity), specific beam instrumentation may be quite useful in understanding and controlling the various collision effects which cause the  $d\mathcal{L}/dE$  spectrum to vary.

If a WISRD-style spectrometer can be successfully operated in the extraction line during collisions, the energy spread of the outgoing bunch can be measured directly. This will potentially give useful real-time monitoring, at least in a relative sense, of the variations of the luminosity spectrum. More traditional 'wire' scanner devices at the end of the linac or in the extraction line[44] will also certainly be needed to measure the energy spectrum of the incoming beams. If a far-forward pair monitor [45] or beamstrahlung photon monitor [46] can be realized, it may be possible to monitor the collision parameters directly bunch to bunch. In any event, the accelerator-based beam instrumentation which is sensitive to the beam parameters at the IP will certainly be needed to help understand the details of the luminosity spectrum.

## 6 Conclusions

Beam instrumentation will be a critical part of a future linear collider physics program. This note has described the physics needs which are foreseen at high energy, as well as a broad outline of the techniques which are being pursued (by the ALCPG IPBI Working Group) to meet these requirements. The single beam polarization is expected to be known to a relative accuracy of  $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 0.25\%$  using Compton polarimetry and forward WW asymmetries. For the beam energy scale, a target of 100 ppm has been set which is expected to be achieved using beam-based spectrometers and radiative return events. The absolute luminosity scale has a target precision of a few tenths of a percent, which can be achieved by monitoring low-angle Bhabha scattering. The most difficult requirement to specify is the knowledge of the luminosity spectrum, partly because the entire spectrum must be understood and there is no single number to characterize this knowledge. In general terms, the relative population of the tail needs to be understood to the 1% level, while the width of the core needs to be known to a precision of 0.1%. The canonical method to measure the

$d\mathcal{L}/dE$  spectrum is acolinearity in forward Bhabha scattering, although this analysis alone is not sufficient.

There are several outstanding conceptual issues which could immediately benefit from additional study:

- **Luminosity spectrum analysis** – A complete and detailed analysis to extract the luminosity spectrum (both tail and core) needs to be performed using realistic beam and detector simulations, backgrounds, and systematic uncertainties. Understanding how the  $d\mathcal{L}/dE$  spectrum can be reconstructed with imperfect knowledge of incoming beam energy distribution, beam offsets, dispersion angles, and other variable collision parameters must be demonstrated.
- **Extraction line studies** – A better understanding of the extraction line environment is needed in order to show that measurements of polarization and beam energy are tenable after the IP.
- **Forward tracking** – A realistic conceptual design for the forward tracking system complete with expected systematic uncertainties on alignments needs to be undertaken. Understanding the backgrounds in this detector, and the impact on both the radiative return and Bhabha acolinearity analysis is also a high priority.
- **Energy width** – Methods for measuring the beam energy distribution at the end of the linac and elsewhere need to be understood. How this information feeds into the  $d\mathcal{L}/dE$  analysis also needs to be more fully explored in conjunction with the complete  $d\mathcal{L}/dE$  analysis listed above.

While this list is by no means exhaustive, these four topics stand out as pressing concerns standing in the way of a true conceptual design to address the beam instrumentation needs of any future linear collider. A program of University based R & D projects has been proposed[47] which includes work on beam instrumentation and addresses some of the items on this list.

## References

- [1] SLD Collaboration, *Phys. Rev. Lett.* **86** (2001) 1162.
- [2] “Linear Collider Physics Resource Book for Snowmass 2001,” SLAC-Report-570 (2001).
- [3] G. Moortgat-Pick, H. M. Steiner, *Int. J. Mod. Phys.* **A15** (2000) 2529. [hep-ex/0004004]
- [4] M. Woods, *Int.J.Mod.Phys.* **A15** (2000) 2529. [hep-ex/0004004]
- [5] P. C. Rowson and M. Woods, SLAC-PUB-8745. [hep-ex/0012055]
- [6] R. Hawkings and K. Monig, DESY 99-157, 1999.

- [7] Kathleen A. Thompson, SLAC-PUB-8716, 2001.
- [8] K. Yokoya and P. Chen. SLAC-PUB-4692, 1988.
- [9] M. Woods, *Int.J.Mod.Phys.* **A13** (1998) 2517. [hep-ex/9802009]
- [10] Y.M. Nosochkov and K. A. Thompson, LCC-0049, 2000.
- [11] Y.M. Nosochkov and T.O. Raubenheimer, SLAC-PUB-8313, 1999.
- [12] V. Gharibyan, N. Meyners, and P. Schuler, LC-DET-2001-047, 2001.
- [13] M. L. Swartz, *Phys.Rev.* **D58** (1998) 014010. [hep-ph/9711447]
- [14] D. V. Onoprienko, SLAC-Report-556, 2000.
- [15] M. Woods, SLAC-PUB-7319, 1996.
- [16] P. C. Rowson, SLAC-PUB-9200, 2002.
- [17] A. Blondel *Phys. Lett.* **B202** (1988) 145.
- [18] F. Cuypers and P. Gambino, *Phys. Lett.* **B388** (1996) 211.
- [19] K. Monig, SNOWMASS-2001-E3009, 2001.
- [20] T. Abe *et al.* (American Linear Collider Working Group),  
“Linear Collider Physics Resource Book for Snowmass 2001,” ppg. 239-253.
- [21] T. Abe *et al.* (American Linear Collider Working Group),  
“Linear Collider Physics Resource Book for Snowmass 2001,” ppg. 109-111.
- [22] [LEP Energy Working Group], in preparation.
- [23] T. Slaton, G. Mazaheri, and T. Shintake, SLAC-PUB-7921, 1998.
- [24] M. Hildreth, private communication.
- [25] J. Kent *et al.*, “Precision Measurements Of The Slc Beam Energy,” SLAC-PUB-4922, *Presented at IEEE Particle Accelerator Conf., Chicago, Ill., Mar 20-23, 1989.*
- [26] S. S. Hertzbach, “Beam energy measurement at a linear collider with an SLC style energy spectrometer,” *Prepared for 5th International Linear Collider Workshop (LCWS 2000), Fermilab, Batavia, Illinois, 24-28 Oct 2000.*
- [27] M. Acciarri *et al.* (L3 Collaboration), *Phys. Lett.* **B454** (1999) 386-398.
- [28] Opal Collaboration, OPAL-PN493, 2001.  
<http://opal.web.cern.ch/Opal/pubs/physnote/html/pn493.html>

- [29] [LEP Collaborations], “Combination procedure for the precise determination of Z boson parameters from results of the LEP experiments.” [hep-ex/0101027]
- [30] P.C. Rowson *et al.*, SLD-NOTE-264, 2000.  
<http://www-sldnt.slac.stanford.edu/sldbb/SLDNotes/sld-note-264.pdf>
- [31] K. Buesser and M. Paganoni, “The Measurement of Luminosity at TESLA,” LC-DET-2001-044 (2001).
- [32] G. Alimonti, “Pair Monitor for Linear Collider,” LCWS 2000 proceedings, p. 748.
- [33] T. Tauchi and K. Yokoya, “Nanometer Beam Size Measurement during collisions at Linear Colliders,” *Phys. Rev.* **E51** (1995) 6119.
- [34] T. Kamon, R. Arnowitt, B. Dutta and V. Khotilovich, “Probing mSUGRA models at linear colliders,” contribution to LCWS Jeju proceedings (2002). [hep-ph/0302249]
- [35] K. Fujii, T. Matsui, and Y. Sumino, *Phys. Rev.* **D50** (1994) 4341.
- [36] D. Cinabro, LCWS Sitges proceedings (1999), p243.  
<http://www.desy.de/~lcnotes/stiges/D.Cinabro-10.ps.gz>
- [37] D. Cinabro Luminosity Spectrum contribution to LCWS Jeju proceedings (2002).
- [38] M. Bataglia contribution to LCWS Jeju proceedings (2002).
- [39] M. N. Frary and D. J. Miller, DESY-92-123A, p379.  
<http://www.hep.ucl.ac.uk/lc/documents/frarymiller.pdf>
- [40] Y. Kurihara, contribution on behalf of the KEK JLC group to First EDFA/DESY workshop, Munich September 1996.
- [41] R. Frey *et al.* in *Summary Report for Snowmass 1996*, eds. D.G. Cassel, L.T. Gennari, and R.H. Siemann (1997). [hep-ph/9704243]
- [42] K. Moenig, LC-PHSM-2000-60-TESLA, contribution to LCWS Jeju proceedings (2002).  
<http://www.desy.de/~lcnotes/2000/060/beamspec.ps.gz>
- [43] M. Bataglia, SNOWMASS-2001-E3015, 2001.
- [44] Y. Nosochkov, T.O. Raubenheimer, SLAC-PUB-8871 (2001).
- [45] M. Saigo contribution to LCWS Jeju proceedings (2002).
- [46] G. Bonvicini, N. Powell, “Beamstrahlung at the NLC,”  
*Submitted to Phys. Rev. E.* [hepex/0304004]
- [47] [http://www.hep.uiuc.edu/LCRD/html\\\_files/proposal.html](http://www.hep.uiuc.edu/LCRD/html\_files/proposal.html)