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Beam Instrumentation Tests for the Linear Collider using the SLAC A-Line and End Station A

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Abstract

The polarized beam for the recent E-158 experiment at SLAC achieved many of the characteristics required for the beam at the NLC. This achievement, together with existing beam instrumentation (BI) capabilities, utilizing spin precession in the A-Line for precise energy measurements, and mimicking beam-beam effects (disruption and beamstrahlung) with an ~10% X_0 target, motivate utilizing the A-Line and End Station A (ESA) facilities to test BI required for a future Linear Collider (LC), in particular for measurements of luminosity, energy and polarization.

1. Introduction

Precise knowledge of the initial state is a distinct advantage for an e^+e^- collider for making precision measurements and for uncovering new physics. This advantage can only be realized, however, if there is adequate instrumentation available to measure the beam properties at the interaction point (IP). A significant complication at the LC is the large beam disruption and beamstrahlung resulting from the intense electromagnetic fields during collision. The luminosity-weighted beam parameters can differ significantly from the average beam parameters measured by the beam instrumentation. A test beam experiment at SLAC's ESA can mimic the beam disruption and beamstrahlung present at the LC, with multiple scattering and bremsstrahlung in a thick (~10% X_0) target. The performance of beam diagnostics planned for the NLC *extraction line* (for example: BPMs for luminosity optimization, an energy spectrometer, a polarimeter) can therefore be tested in ESA downstream of a thick target.

Table 1 compares the achieved beam parameters for E-158[1] with those proposed for the 500-GeV NLC machine. The pulse charge for the E-158 beam approaches what is required for NLC. It is a factor 15 higher than that used for SLC operation and has a pulse structure similar to that proposed for NLC. The E-158 beam power can exceed 0.5 MW (at 120Hz operation) and achieves remarkable stability. The jitter performance is noted in Table 1 and the numbers quoted were routinely achieved.

Table 1: Beam parameters achieved for E-158, and proposed for NLC-500.

Parameter	E-158	NLC
Charge/Pulse	6×10^{11}	14.4×10^{11}
Rep Rate	120 Hz	120 Hz
Energy	45 GeV	250 GeV
Pulse Train	270 ns	267 ns
Microbunch Spacing	0.35 ns	1.4 ns
Beam Loading	13%	22%
Energy Spread	0.15%	0.16%
e^- Polarization	85%	>80%
Intensity Jitter	0.5%	0.5%
Energy Jitter	0.03%	0.3%
Transverse Jitter	5% of spotsize (x or y)	22% of x spotsize, 50% of y spotsize

In this Letter-of-Intent, we describe the capabilities that the SLAC A-Line and ESA provide for testing key beam instrumentation detectors and techniques to be employed at a future LC. There are significant R&D efforts in the U.S.[2] and world-wide[3] to design and develop (IP) BI for the LC. Currently, these efforts are mostly focused on simulations, with some detector development and beam tests taking place. This work will evolve to the need for beam tests described in this LOI. The program of beam tests we describe would begin with a 1-week beam test in FY05 that would require only modest changes to the existing beamline and instrumentation. The beam tests can be carried out at (10-30) Hz repetition rate over a range of energies from (20-45) GeV, and can be parasitic to PEP-II operation. Most of the tests can be carried out at 10Hz and 30 GeV.

2. SLAC's A-Line and End Station A

The beam and experimental setup for the recent E-158 experiment is shown in Figures 1 and 2. The polarized source consists of a polarized laser system and a photocathode electron gun. The beam from the source is longitudinally polarized and is accelerated to either 45 GeV or 48 GeV in the Linac, bypassing the Damping Rings. At the end of the SLAC Linac, the invariant emittance has been measured to be
$\gamma\varepsilon_x = \gamma\varepsilon_y = 13.2 \times 10^{-5}$ m-rad, giving $\varepsilon_x = \varepsilon_y = 1.5 \times 10^{-9}$ m-rad at E=45.48 GeV. Synchrotron radiation in the 24.5^0 bend in the A-line increases the horizontal emittance by a factor 25 at this energy. For the beam tests considered in this LOI, we plan to run with

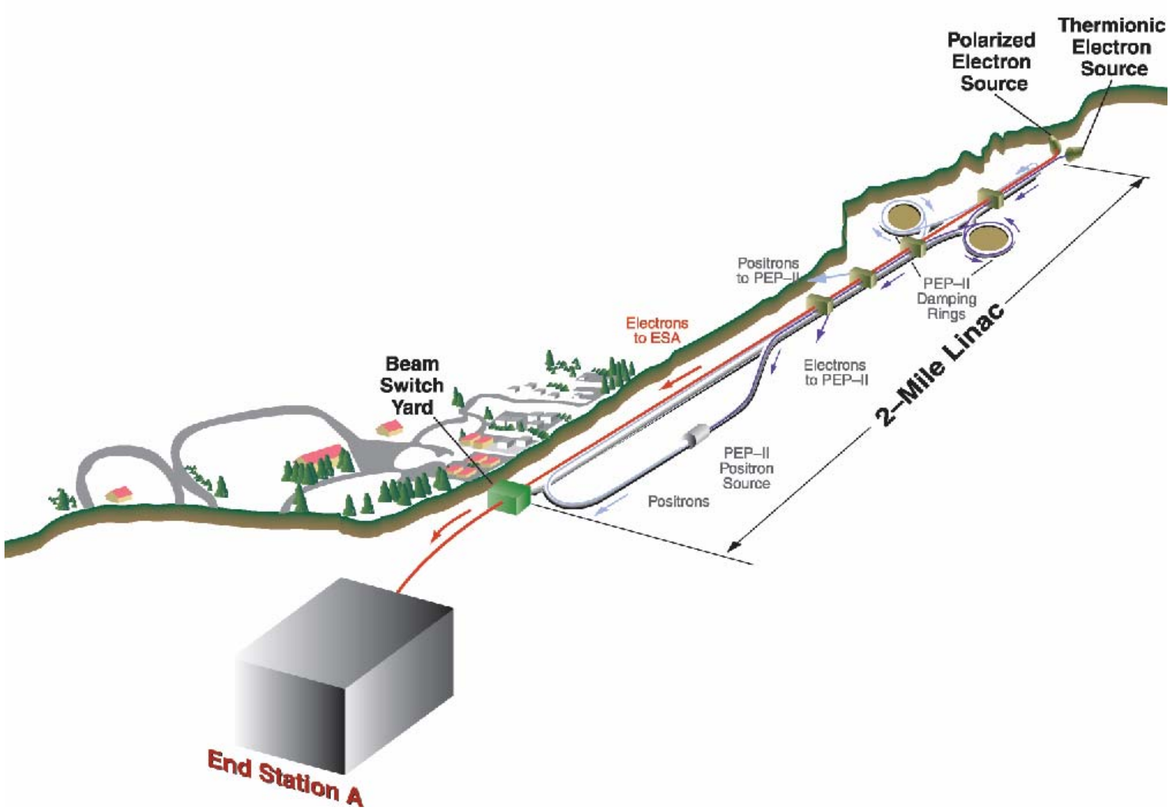

Figure 1: SLAC Facility for Polarized Beams to End Station A

beam energies in the range (20–45) GeV. Emittance increase in the A-Line at 30 GeV and below is negligible. The beam tests would use beam intensities of $5 \cdot 10^{11}$ in a 300ns train, at pulse repetition rates of (10-30) Hz. The A-Line bend angle results in 180-degree spin precession every 3.237 GeV, making this a useful diagnostic for precise beam energy measurements. End Station A is 60 meters long (Figure 2) and we envision using this region for installing additional beam diagnostics for the LC BI beam tests.

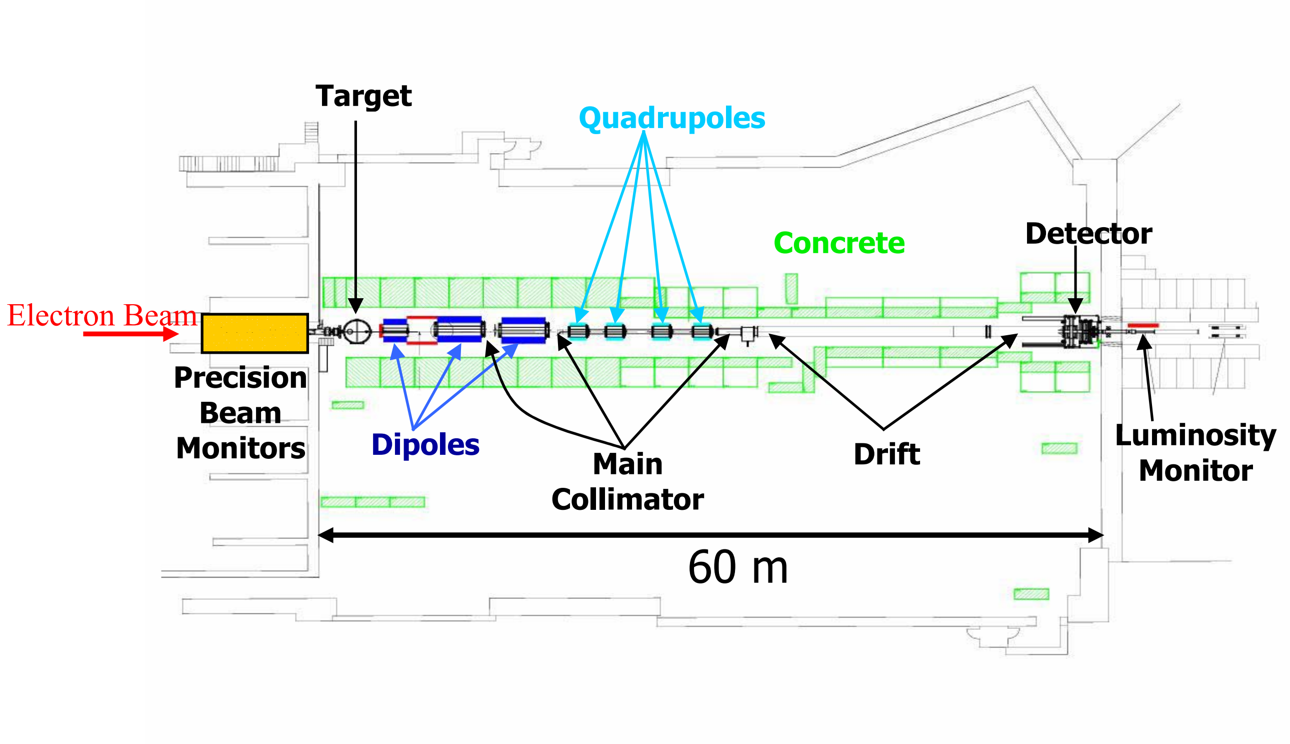

Figure 2: E-158 experimental setup in End Station A

A schematic of the beam diagnostics read out by the E-158 data acquisition (DAQ) is shown in Figure 3. A pair of rf BPMs (Position BPMs) is located two meters in front of a liquid hydrogen (LH2) target at the front end of ESA. One meter upstream of the LH2 target is a wire array used for spotsize measurements. Forty meters upstream of this location is a 2nd pair of rf BPMs (Angle BPMs). Four toroids are located in the region of the Position BPMs. Further upstream at dispersive locations ($\eta \sim$ 500mm) in the A-Line are two additional rf BPMs used for energy measurements. Momentum slits halfway through the A-Line at the highest dispersion point ($\eta \sim$ 5 meters) have a full aperture of 2% momentum acceptance. Additional beam diagnostics available include:

i) a MOLLER polarimeter, with a target foil adjacent to the Wire Array.

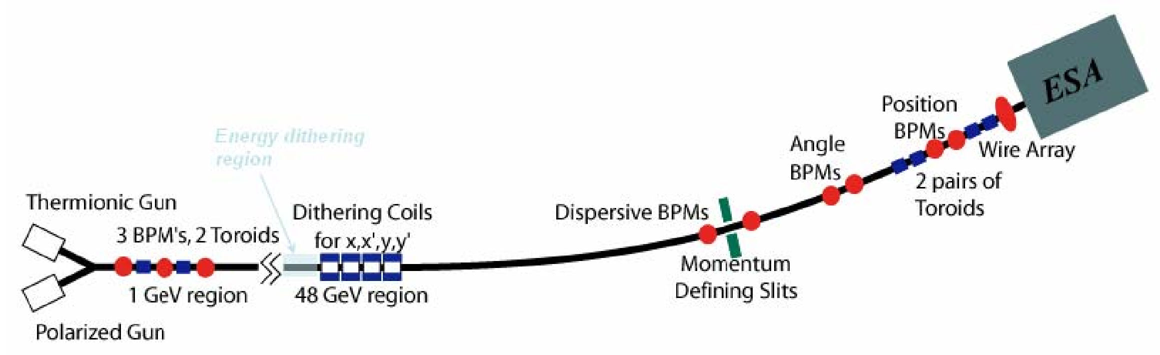

Figure 3: Beam Diagnostics (toroids, BPMs, wire array) for E-158.

ii) an energy diagnostic, useful for energy spread and temporal energy profile measurements, from a synchrotron light monitor (SLM). The SLM system has a gated ccd camera viewing visible synchrotron radiation from one of the A-line bend magnets, which has been imaged from a high dispersion point. Data from this device is shown in Figure 4, showing the temporal profile over the 300-ns pulse train of the beam energy and energy spread.

iii) parallel electronic readout of the BPMs indicated here by the accelerator control system. Also, there are additional rf bpms, one stripline BPM (with 5-meter dispersion), several toroids and many beam loss monitors in the A-line that are readout by the accelerator control system and not by the E158 DAQ.

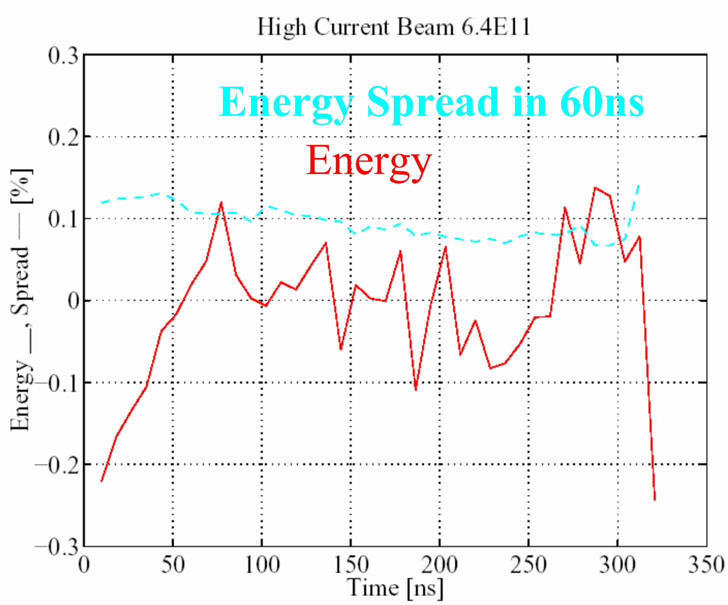

Figure 4: A-Line Synchrotron Light Monitor measurement of beam energy and energy spread during 300-ns pulse train. A gated ccd camera is used with a 60-ns gate width for this measurement. Beam intensity was 6.4 x 10^{11} electrons in the train.

The resolutions for the BPM and toroid beam diagnostics are shown in Figures 5, 6 and 7.[4] These are determined by measuring the beam jitter with redundant devices. The Position and Angle rf BPMs achieve resolutions of 2 microns per pulse. The energy BPMs achieve 1 MeV resolution per pulse, and the toroids achieve an intensity resolution of 30 parts per million (ppm) per pulse.

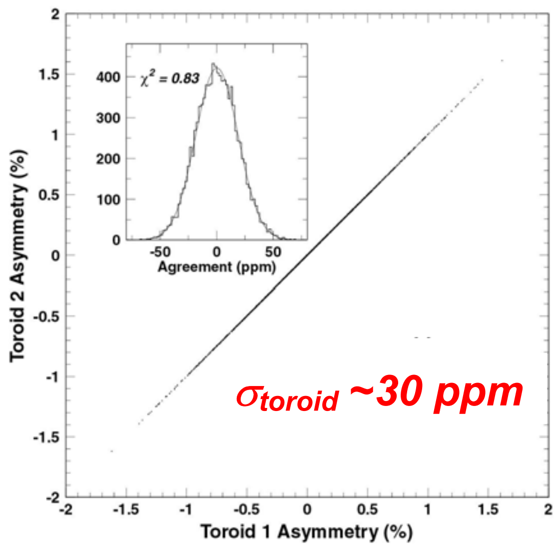

Figure 5: 30ppm toroid resolution

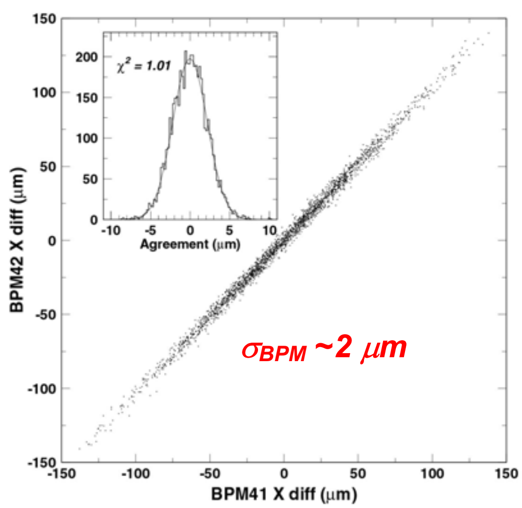

Figure 6: 2 micron BPM resolution

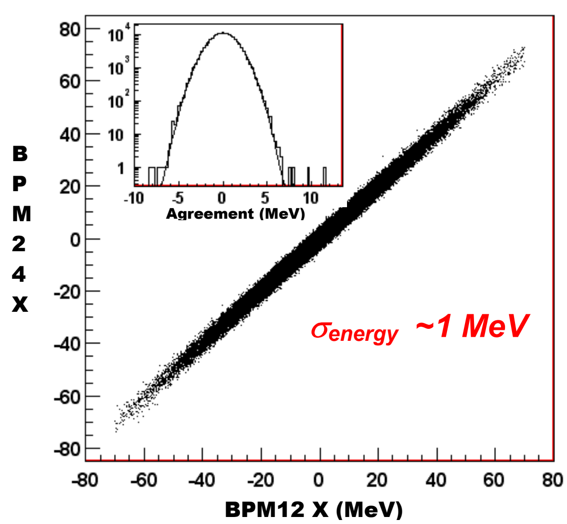

Figure 7: 1 MeV energy resolution

3. Luminosity and Luminosity spectrum measurements; and Beam-Beam Effects

Detectors for the absolute luminosity measurements required by the LC physics program probably do not need the high intensity and pulse train structure that are features of the beam capabilities for ESA. However, ESA beam tests may be useful for the high rate luminosity detectors required by accelerator operations for optimizing and maintaining luminosity. Such detectors would be the *pair* and *radiative Bhabha* detectors at small scattering angles. Instrumentation relevant for determination of the luminosity spectrum and instrumentation affected from beam-beam effects (disruption and beamstrahlung) will benefit significantly from beam tests in ESA. Additionally, there is a significant ongoing R&D effort to implement a fast intra-train feedback to stabilize the colliding e^+e^- beams at the nanometer level.[5] This FONT (Feedback On Nanosecond Timescales) would utilize fast bpms ~ 2-3 meters downstream of the IP to measure the deflection angle of the outgoing beam at the head of a train, and then employ fast kickers to center the colliding beams for the following train buckets. The performance characteristics of such BPMs can be tested in ESA downstream of a 10% X_0 target. FONT may be needed in the NLC design to correct residual beam offsets at the 5-10 nanometer level. In the TESLA design, FONT is considered essential though it can be much slower because of the 337-ns bunch spacing compared to 1.4 ns at NLC. For both machines, *extraction line* BPMs to measure deflection angles are required for slower feedbacks to center the colliding trains (5Hz train collision rate for TESLA and 120Hz for NLC). Typical beam-beam deflection scans are shown in Figure 8 for the NLC-500 and TESLA-500 parameter sets.

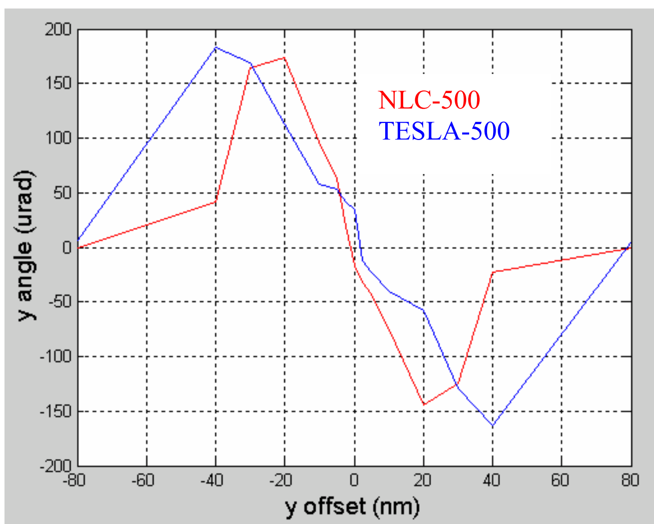

Figure 8: Deflection scans for the NLC-500 and TESLA-500 parameter sets.

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, about 0.1% of the incoming beam energy was lost to beamstrahlung photons, while for the baseline NLC-500 design this loss is ~5% 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. The primary method envisioned to measure the luminosity spectrum is to consider the acolinearity of Bhabha events produced at the IP.[6] However, there are significant complications to extracting the full d*L*/d*E* spectrum from simply considering the acolinearity angle alone. It is likely that additional information from direct beam measurements will be necessary.[2]

Table 2 compares the incoming and outgoing beam characteristics for a beam test in ESA and for collisions at NLC-500. While the beam spotsize at the ESA Target is vastly different from its size at the NLC IP, the outgoing beam divergences are comparable. This results from the multiple scattering angles in the ESA target being comparable to the disruption angles at NLC-500. Additionally, the energy loss due to bremssstrahlung and the resulting electron energy spectrum for the ESA experiment are comparable to the beamstrahlung energy loss and disrupted electron energy spectrum at NLC-500.

Table 2: Comparison of Beam-Target and Beam-Beam effects at ESA and NLC-500

	ESA Beam Test w/ 10% X_0 Target	**NLC-500**
Beam Energy (GeV)	25 GeV	250 GeV
Incoming beam divergence: σ(x angle); σ(y angle)	3 μrad; 3 μrad	40 μrad; 30 μrad
RMS spotsize at Target/IP	500 μm (x); 500 μm (y)	0.24 μm (x); 0.003 μm (y)
Outgoing beam divergence: σ(x angle); σ(y angle)	170 μrad; 170 μrad	240 μrad; 100 μrad
RMS spotsize 3 meters downstream	700 μm (x); 700 μm (y)	700 μm (x); 300 μm (y)
(Brems/Beam)strahlung Energy	10%	7%

The following beam tests for luminosity and luminosity spectra measurements, and for assessing the impact of beam-beam effects on *extraction line* instrumentation, can be done at SLAC's End Station A:

a. Test BPM performance in the presence of beamstrahlung and disrupted beams, mimicking these beam-beam effects with bremsstrahlung and multiple scattering in a thick (~10% X_0) target.
b. Test the temporal performance of *extraction line* BPMs over the 300-ns train, with and without the presence of a target for mimicking beam-beam effects.
c. Test high rate luminosity detectors for realtime optimization of luminosity (pair and radiative Bhabha detectors) . Test their temporal performance.
d. Study energy spectrometer performance in the presence of a thick target. Can a synchrotron-stripe spectrometer measure the disrupted energy spectrum? Can it resolve the beam energy spread from the disrupted spectrum?
e. Study the polarimeter performance in the presence of a thick target.

f. Study the performance of other *extraction line* diagnostics in the presence of a thick target.

4. Energy and Energy Spread Measurements

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 LC, however, as the resonant depolarization technique used in storage rings cannot be applied. The precision necessary for the energy range $2m_t \prec \sqrt{\mathrm{s}} \prec 1\,\mathrm{TeV}$ is much more modest than the LEP energy scale, and a relative precision of 10^{-4} or 100 ppm appears to be adequate for the baseline program,[7] in particular for the top mass.[8] 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 $e^+e^- \to Z^0\gamma$ or W-pair production also have potential for measurements of the beam energy and are being studied, though they do not replace the need for real-time energy measurements. In addition to measuring the absolute energy scale, there is a strong need to make measurements of the energy spread of the incoming beams to facilitate determinations of the luminosity spectrum and the luminosity-weighted beam energy. 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 spread of the beam is expected to be around 0.3%. Good knowledge of this energy distribution is a necessary component of any luminosity spectrum, L(E), analysis. The Bhabha acolinearity used in the L(E) analysis should have the capability to extract dn/dE from the physics data. But that analysis will benefit from direct, real-time measurements of the incoming beam energy spread.

The deflection of a charged particle traversing a magnetic field is a well established method for measuring a particle's momentum. For the NLC, it is proposed to build two independent spectrometers each capable of 100ppm 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 LEPII to cross check the energy scale for the W mass measurement to a precision of 200ppm.[9] At a future LC, this device would use RF BPMs which can potentially achieve precisions on the transverse beam position approaching 10nm.[10] Located upstream of the primary IP, concerns about emmittance dilution restrict the possible spectrometer bend angle to something less than 100 microradians. RF BPMs capable of 10nm precision and stability would be able to make a 100ppm measurement of E_{beam} with a lever arm on the order of meters. Fast (ideally bunch-by-bunch) measurements within a train from these BPMs is also desirable to resolve energy variations within the train.

At the SLC, the WISRD spectrometer was successfully used to make beam energy measurements at 120Hz with a precision of 250ppm at E_{beam} = 45 GeV.[11] The SLC WISRD consisted of a strong vertical analyzing dipole flanked by two weaker horizontal dipole magnets. The synchrotron radiation stripes produced by these two weaker dipoles were detected downstream on wire arrays, such that the deflection angle of the beam in the analyzing magnet could be directly monitored. A WISRD-style energy spectrometer, with some modifications, may meet the 100ppm goal for the LC if care is taken to design the system into the machine at an early stage.[12] 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. The location of the WISRD 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.

The following beam tests for LC energy and energy spread measurements can be done at SLAC's A-Line and End Station A:

i) commission a BPM-based energy spectrometer and a synchrotron-stripe energy spectrometer, and compare their beam energy measurements.

ii) scan the beam energy in the A-line from 20 GeV to 30 GeV (reproducing the beam orbit on the A-line bpms at each energy point), while measuring the longitudinal polarization of the beam in ESA with the existing MOLLER polarimeter. Use spin precession to determine the beam energy and compare with results from the BPM or synchrotron stripe spectrometers. (Also compare with the flip coil measurement of the reference bend magnet and with the power supply currents for the A-line bend magnets.)

iii) measure the energy jitter with the new spectrometers, and compare with the 1-MeV resolution measurements (<30ppm) from the existing energy bpms.

iv) measure the temporal profile of the beam energy along the 300-ns train with the new spectrometers, and compare with results from the existing gated CCD camera viewing viewing visible synchrotron radiation from an A-line bend magnet. Also measure the temporal profile of the energy spread and energy jitter.

5. Polarization Measurement

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.[13] Similarly, polarization is expected to play a key role at a future LC for interpreting new physics signals and for making precision measurements.[14,15] The baseline designs for the NLC/JLC and TESLA machines provide for polarized electron beams with $P \sim (80-90)\%$ expected. Initially the positron beams will be unpolarized, although there is significant interest and physics motivation for realizing polarized positron beams in future upgrades.

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.[16,17] High statistics Giga-Z running at the Z-pole would benefit from polarimetry at the 0.1% level.[18]

SLD's Compton polarimeter achieved a precision of 0.5%. At the NLC, the primary polarimeter measurement will be performed by a Compton polarimeter located in the *extraction line* downstream from the IP.[19] An accuracy of $\Delta P/P = 0.25\%$ should be achievable,[17] extrapolating from experience with the SLD polarimeter. A location downstream of the IP is chosen so that beam-beam depolarization effects[20,21] 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.

The following beam tests for LC polarimetry could be done in End Station A:

i) Install a Compton polarimeter, reusing much of the SLD polarimeter system. Make the necessary upgrades to achieve 0.25% polarimetry, making redundant measurements with complementary detectors to determine the systematic error.[22]

ii) Measure the temporal dependence of the polarization along the 300-ns train.

6. Conclusions and Request to SLAC's EPAC

The high-intensity polarized beam at SLAC's A-Line and End Station A provide beam characteristics satisfying many aspects of the beam for the NLC. We have described many beam tests needed to test IP beam instrumentation for a future Linear Collider. These tests are needed to ensure that that the LC physics program achieves its ambitious goals. We anticipate carrying out such beam tests in FY05, FY06 and FY07. During FY04 we are focusing on simulation and design efforts. The program of beam tests would begin with a 1-week beam test in FY05, requiring only modest upgrades to existing instrumentation. We envision carrying out 1-2 week beam tests in each of FY06 and FY07. The FY05 test would include installing a bpm doublet or triplet downstream of a target station in ESA. The bpm performance characteristics for a long pulse train, with and without a 10% radiator in front of it for mimicking beam-beam effects, would be studied. Additional studies in FY05 could include studies of A-Line spin precession as an energy measurement diagnostic using the existing Moller polarimeter and other existing energy diagnostics (flip coil and magnet power supply currents).

This work is taking place in cooperation with the ALCPG (American Linear Collider Physics Group) Working Groups on IP Beam Instrumentation[23] and Test Beams,[24] with the NLC Beam Delivery Group,[25] and with the University Program of Accelerator and Detector Research for the Linear Collider, being funded by the DOE and NSF.[26] In FY03, 4 of the 14 funded DOE University projects for LC Detector Research were for IP Beam Instrumentation. Continuations of these projects require beam tests, some of which have been described in this LOI.

Our requests to the EPAC are the following:

i) Recognize the importance of SLAC's Polarized Electron Source, A-Line and End Station A facilities for LC BI beam tests. (Particularly since there currently are no approved physics experiments at SLAC requiring either a polarized beam or high power beam to End Station A, it is important that SLAC retain the capability to provide such beams.)

ii) Recommend that SLAC take into consideration LC BI beam tests, when modifying the A-Line and ESA beamlines, or the Polarized Source.

iii) Encourage the development of (full technical) beam test proposals for LC BI, using the SLAC A-Line and ESA facilities. In particular, we request a recommendation encouraging a 1-week beam test in End Station A in FY05.

iv) Recommend that SLAC include funding for LC BI beam tests in End Station A in planning for the FY05 and FY06 budgets. Recommend that SLAC allow for a 1-week beam test in End Station A in FY05 in the long-range accelerator planning.

References

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   Also see:
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3. For example, the UK has a strong group focusing on beam delivery and the machine-detector interface at the LC. A recent proposal by them to their funding agency is available at http://www.pp.rhul.ac.uk/~blair/LC_BDS_proposal/, and includes a description of some beam tests that are best done using the SLAC A-Line and ESA.
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7. The precision required for energy measurements is discussed in detail in Reference [2]. Improved energy measurement precision to 50ppm or better would be needed to fully exploit the statistical precision that could be achieved for a precise measurement of the W mass or for a very precise weak mixing angle measurement at a Giga-Z program.
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26. The University R&D efforts funded by the DOE (LCRD) and NSF (UCLC) are described at these web links:
    http://www.hep.uiuc.edu/LCRD/html_files/index.html
    http://www.lns.cornell.edu/public/LC/UCLC/