Beam Instrumentation Tests for the Linear Collider

SLAC EPAC Meeting
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Luminosity, Energy and Polarization measurements at the Linear Collider
(LC-LEP measurements)

SLAC A-Line and End Station A Facility
  Beam Characteristics and Comparison with NLC Beam
  Beam Diagnostics

LC-LEP Beam Tests at SLAC

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

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Luminosity, Energy and Polarization measurements at the Linear Collider
(LC-LEP measurements)
WG Scope ➔ Beam Instrumentation required for LC Physics

**Principle Topics** $(L,E,P)$
- Luminosity, luminosity spectrum $(dL/dE)$
- Energy scale and width
- Polarization

**Also**
- Instrumentation for optimizing Luminosity
  - IP BPMs for fast feedback and feedforward
  - detectors for pairs, beamstrahlung, radiative Bhabhas

M. Woods (SLAC)
LC-LEP Measurement Goals

**Luminosity, Luminosity Spectrum**

- Total cross sections: absolute $\delta L/L$ to $\sim 0.1\%$
- Z-pole calibration scan for Giga-Z: relative $\delta L/L$ to $\sim 0.02\%$
- threshold scans (ex. top mass): relative $\delta L/L$ to 1%
  + $L(E)$ spectrum: core width to $< 0.1\%$ and tail population to $< 1\%$

**Energy**

- Top mass: 200 ppm (35 MeV)
- Higgs mass: 200 ppm (25 MeV for 120 GeV Higgs)
- W mass: 50 ppm (4 MeV) ??
- ‘Giga’-Z $A_{LR}$: 200 ppm (20 MeV) (comparable to $\sim 0.25\%$ polarimetry)
  50 ppm (5 MeV) (for sub-0.1% polarimetry with e+ pol) ??

**Polarization**

- Standard Model asymmetries: $< 0.5\%$
- ‘Giga’-Z $A_{LR}$: $< 0.25\%$
Beamstrahlung at the Linear Collider

~7% of the beam energy gets radiated into photons due to beamstrahlung (at SLC this was 0.1%)
The beam diagnostics measure $\langle E \rangle$, $\langle P \rangle$. For physics we need to know $\langle E \rangle_{\text{lum-wt}}$, $\langle P \rangle_{\text{lum-wt}}$.

\[
\langle E \rangle_{\text{lum-wt}} \neq \langle E \rangle \\
\langle P \rangle_{\text{lum-wt}} \neq \langle P \rangle
\]

Strategy is to use a combination of beam diagnostics and physics-based detector measurements. *Need to understand $L(E)$ spectrum and how it is affected from beamstrahlung and energy spread, as well as from initial state radiation.*

→ 100-200 ppm physics goal for determining $\langle E \rangle_{\text{lum-wt}}$

<< 3000 ppm energy spread

<<< 70,000 ppm energy loss due to beamstrahlung!

How well the luminosity-weighted quantities can be determined depends on the beam parameters at the IP, as well as on the intrinsic capabilities of the polarimeter and the energy spectrometers.
**LC Detector Measurements of L(E), \(<E>_{\text{lum-wt}}\), \(<P>_{\text{lum-wt}}\)**

**Luminosity Spectrum, L(E)**
Bhabha Acolinearity:

\[
\theta_A = \theta_1 - \theta_2
\]
\[
\Delta p = p_1 - p_2
\]
\[
\frac{\Delta p}{p_{\text{beam}}} \approx \frac{\theta_A}{\sin \theta}
\]

\(<E>_{\text{lum-wt}}\)
Radiative return to Z events
W-pair events

\(<P>_{\text{lum-wt}}\)
Asymmetry in forward W-pairs

These techniques don’t replace the need for *real-time* beam-based measurements. Want complementary and/or combined analyses with beam-based measurements.
For this study, turn off ISR and beamstrahlung and only consider beam energy spread.

\[ \langle E_{cm} \rangle_{\text{lum-wt}} = \frac{\sqrt{s'} - 500 \text{ GeV}}{500 \text{ GeV}} \approx 500 \text{ppm} \]

Bhabha acolinearity analysis won’t help resolve this bias.
Instrumentation for Luminosity, Luminosity Spectra and Luminosity Tuning

**Luminosity**
Bhabha LuMon detector from 40-120 mrad

**Luminosity Spectrum**
Bhabha acolinearity measurements using forward tracking and calorimetry from 120-400 mrad
+ additional input from beam energy, energy spread and energy spectrum measurements

**Luminosity Tuning**
Pair LuMon detector from 5-40 mrad
Beamstrahlung detector from 1-2 mrad (further downstream)
IP BPMs
Forward Tracking, Calorimetry and Masking
(for NLC Silicon Detector)

Forward Tracking, Calorimetry and Masking
(for NLC Silicon Detector)

Bhabha LuMon
Tungsten
Pair LuMon
LowZ Mask
Exit radius
2cm @ 3.5m
Support Tube
ECAL
HCAL
YOKE

incoming e+

outgoing e−

IP BPMs for fast feedback
and feed forward @ ~z = 3.5 meters
Using Pairs and Beamstrahlung for Luminosity Tuning

7 degrees-of-freedom for colliding bunches:
- individual spotsizes (4)
- relative offset (2)
- relative tilt of bunches (1)

2 promising detector techniques for determining beam offsets and individual beamsizes:

1. Angular distributions of low energy $e^+e^-$ pairs from 2-photon processes

2. Measuring polarization of the beamstrahlung emitted at angles of (1-2) mrad.
Using IP BPMs for Luminosity Tuning

**Deflection angle vs vertical offset**

**Luminosity vs vertical offset**

**Slow (inter-train) and fast (ns-timescale intra-train) feedbacks are planned**

Two of the highest risk factors for achieving LC design luminosity are:

i) reliance on IP feedbacks and

ii) effects of backgrounds (beam-beam and other) on detectors and beam instrumentation

Fast IP Beam diagnostics **must** work as planned and be robust against backgrounds
Instrumentation for Energy, Energy Spread and disrupted Energy Spectrum

**Energy**
- BPM spectrometer (upstream of IP)
- Synchrotron Stripe spectrometer (in extraction line)

**Energy Spread**
- Synchrotron Stripe spectrometer (in extraction line)
- Wire scanner at high dispersion point in extraction line chicane

**Disrupted Energy Spectrum**
- Synchrotron Stripe spectrometer (in extraction line)
- Wire scanner at high dispersion point in extraction line chicane

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**BEAM OPTICAL ELEMENTS**
- Electron ELS Shown

**Initial Stripe**
- **Final Stripe**
- **WISRD**
- **Wire Arrays**
- **Quadrupole Doublet**
- **Spectrometer Magnet**
- **Vertical**
- **Horizontal Bends for Synchrotron Radiation**

**Proposed BPM spectrometer at NLC**

**Synchrotron Stripe Spectrometer at SLC**
Instrumentation for Polarimetry

Compton Polarimeter in Extraction Line

Input Laser Light 11.5 mrad

Beam Stay Clear 1 mrad from IP

Chicane bend magnets

Compton IP

Thin Radiator

Back Scattered Photons

Electron beam

107 GeV

125 GeV

93.8 GeV positrons

100 GeV electrons

2 cm

13 cm

30 Meters

4 cm

25 GeV electron

37.5 GeV

7 cm

Compton Electron Detector

Pair Spectrometer Positron Detector

Ken Moffett
**Luminosity**

- Fast Gas Cherenkov Calorimeter (*Iowa St.*)
- Parallel Plate Avalanche, Secondary Emission Detectors (*Iowa*)
- Large Angle Beamstrahlung Monitor (*Wayne St.*)
- 3d Si Detector for Pair Monitor (*Hawaii*)

**Energy**

- Synchrotron Stripe Spectrometer (*Oregon, UMass*)
- rf BPM Spectrometer (*Notre Dame, UC Berkeley*)

**Polarization**

- Quartz Fiber Calorimeter; W-pair asymmetry (*Iowa*)
- Background study (*Tufts*)
- Quartz Fiber Detector; transverse polarization (*Tennessee*)
SLAC A-Line and End Station A Facility
for LC-LEP measurements
SLAC A-Line and End Station A Facility

- Beam Characteristics and Comparison with NLC Beam
- Beam Diagnostics
## Beam Parameters for SLAC E-158 and NLC-500

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SLAC E-158</th>
<th>NLC-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge/Train</td>
<td>$6 \times 10^{11}$</td>
<td>$14.4 \times 10^{11}$</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>120 Hz</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Energy</td>
<td>45 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>e(^{-}) Polarization</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Train Length</td>
<td>270 ns</td>
<td>267 ns</td>
</tr>
<tr>
<td>Microbunch spacing</td>
<td>0.3 ns</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>Beam Loading</td>
<td>13%</td>
<td>22%</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.15%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Intensity Jitter</td>
<td>0.5% rms</td>
<td>0.5% rms</td>
</tr>
<tr>
<td>Energy Jitter</td>
<td>0.03% rms</td>
<td>0.3% rms</td>
</tr>
<tr>
<td>Transverse Jitter</td>
<td>5% of spotsize (x or y)</td>
<td>22% of x spotsize, 50% of y spotsize</td>
</tr>
</tbody>
</table>
Use 178.5MHz SHB cavity

Bunch Train with
- 5.6ns spacing
- ~$10^{10}$ bunch charge

But, beam in LINAC is unstable.
- some evidence for beam breakup
- needs further study

PPRC is starting a new R&D project to achieve 714MHz modulation (1.4ns bunch spacing) of the Long Pulse laser used for the Source
- will use an electro-optic modulator driven with 714MHz rf
- will experiment both with intra-cavity modulation and an external modulator
Beam Diagnostics for SLAC E-158

$\sigma_{\text{energy}} \sim 1 \text{ MeV}$

$\sigma_{\text{toroid}} \sim 30 \text{ ppm}$

$\sigma_{\text{BPM}} \sim 2 \text{ microns}$
A-Line Synchrotron Light Monitor (SLM)

Energy and Energy spread (in MeV) in 60-ns time slice along the 300ns train for 45 GeV beam
End Station A configured for E-158
LC-LEP Beam Tests at SLAC
BPM Tests
(Energy Spectrometer BPMs and IP BPMs)

1. **Characterize performance of LC BPMs**
   Temporal response and resolution; compare with existing high resolution diagnostics (SLM at high dispersion point and wire array at target)

2. **Mimick ‘beamstrahlung and disruption’**
   for IP bpm using a thick target in ESA; compare LC bpm measurement 4 meters downstream of target with precision upstream bpm

Beams can have temporal ‘banana’ shape in position, angle, energy
### Accelerator Facilities for LC BPM Tests

<table>
<thead>
<tr>
<th></th>
<th>NLC-500</th>
<th>ESA (SLAC)</th>
<th>NLCTA (SLAC)</th>
<th>FFTB (SLAC)</th>
<th>ATF (KEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy</strong></td>
<td>250 GeV</td>
<td>25 GeV</td>
<td>65 MeV</td>
<td>25 GeV</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td><strong>Bunch charge per 1.4ns</strong></td>
<td>0.75 x 10¹⁰</td>
<td>0.25 x 10¹⁰</td>
<td>10⁹</td>
<td>10¹⁰</td>
<td>10⁹</td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td>1.4ns</td>
<td>0.36ns*</td>
<td>0.09</td>
<td>-</td>
<td>2.8 ns</td>
</tr>
<tr>
<td><strong># bunches per train</strong></td>
<td>190</td>
<td>830</td>
<td>1900</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td><strong>Train length</strong></td>
<td>267 ns</td>
<td>300 ns</td>
<td>170 ns</td>
<td>-</td>
<td>60 ns †</td>
</tr>
<tr>
<td><strong>IP BPM type</strong></td>
<td>Stripline</td>
<td>Stripline</td>
<td>Button</td>
<td>Stripline</td>
<td>rf cavity</td>
</tr>
</tbody>
</table>

*new PPRC project is attempting to produce 714MHz modulation of long pulse beam
†ATF will attempt 3-train operation with 60-ns gaps between trains for 300-ns train length
Comparison of Beam Spotsizes and Divergences at NLC-500 and ESA (w/ 10% $X_0$ target)

<table>
<thead>
<tr>
<th></th>
<th>NLC-500</th>
<th>ESA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy</strong></td>
<td>250 GeV</td>
<td>25 GeV</td>
</tr>
<tr>
<td><strong>Incoming beam divergence (x,y)</strong></td>
<td>3 µrad; 3 µrad</td>
<td>40 µrad; 30 µrad</td>
</tr>
<tr>
<td><strong>Outgoing beam divergence (x,y)</strong></td>
<td>170 µrad; 170 µrad</td>
<td>240 µrad; 100 µrad</td>
</tr>
<tr>
<td><strong>RMS spotsizes at IP,Target (x,y)</strong></td>
<td>500 µm; 500 µm</td>
<td>0.24 µm; 0.003 µm</td>
</tr>
<tr>
<td><strong>RMS spotsizes @ z=3.5m (x,y)</strong></td>
<td>710 µm; 710 µm</td>
<td>840 µm; 350 µm</td>
</tr>
</tbody>
</table>

Similar divergences and spotsizes at IP BPM location
NLC-500  
ESA-25 GeV

**Photon Distributions downstream of IP(Target)**

<table>
<thead>
<tr>
<th></th>
<th>ESA-25 GeV</th>
<th>NLC-500</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy</strong></td>
<td>25 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td><strong>#photons/electron</strong></td>
<td>1.34</td>
<td>1.60</td>
</tr>
<tr>
<td><strong>&lt;E_γ&gt;/E_{beam}</strong></td>
<td>0.068</td>
<td>0.041</td>
</tr>
<tr>
<td><strong>ΔE/E_{beam}</strong></td>
<td>0.092</td>
<td>0.066</td>
</tr>
<tr>
<td><strong>&lt;E_γ&gt;</strong></td>
<td>1.7 GeV</td>
<td>10.3 GeV</td>
</tr>
</tbody>
</table>
Beam Tests for Pair detectors

Test performance of high rate pair detector
- use thinner target to match rates and hit density
- test temporal response over 300ns train
Beam Tests for Synchrotron Detectors
(for energy spectrometer, possibly for beamstrahlung detector)

Improve instrumentation for existing SLM in A-Line

Commission new synchrotron stripe detectors in ESA
  • Mirrors and ccds for visible SR
  • Quartz fibers w/ multi-anode PMT readout for ~MeV SR
  • test capability for resolving beam energy spread and hard edge at $E = E_{\text{incoming}}$

![Graph showing NLC-500 and ESA-25GeV with energy spread and energy E/E_{beam} ranges]
Implement both BPM and synchrotron stripe energy spectrometers.
• Compare their performance directly, including capabilities for resolving energy variations along 300-ns train
• Compare energy jitter and energy temporal profile with existing instrumentation using BPMs and the SLM at high dispersion points in the A-Line

24.5-degree A-line bend angle gives 180-degree spin precession every “3.237” GeV
• Use energy scans across 2 or 3 zero-crossings of the polarization, where the beam longitudinal polarization is measured with a Moller or Compton polarimeter. Compare new energy spectrometer results with polarization results. (Can also check comparison with A-line flip coil and power supply currents.) 10^{-3} accuracy from spin precession should be possible; whether 100-200 ppm is feasible needs study.
Polarimetry Beam Tests

Install a Compton polarimeter

- Reuse hardware from SLD Compton polarimeter
- Commission new detectors and make independent asymmetry measurements with complementary detectors to evaluate systematics
  - compare electron and photon measurements
  - compare counting mode versus integrating mode
- Measure temporal dependence of polarization along the 300-ns train
Requests to EPAC

1. **Recognize importance of SLAC’s Polarized Electron Source, A-Line and End Station A facilities for LC-LEP beam tests.** (Currently there are no approved physics experiments at SLAC requiring a polarized beam or a high power long-pulse beam.)

2. **Recommend that SLAC take into consideration LC-LEP beam tests, when modifying the A-Line and ESA beamlines, or the Polarized Source.** (Also need compatibility with Linac modifications for LCLS.)

3. **Encourage the development of (full technical) proposals for LC-LEP beam bests.** In particular, we request a recommendation encouraging a 1-week beam test in FY05.

4. **Recommend that SLAC include funding for LC-LEP beam tests in planning for the FY05 and FY06 budgets.** Recommend that SLAC allow for a 1-week beam test in FY05 and 1-2 week beam tests in FY06 and FY07 in the long-range accelerator planning.
Conclusions

We have presented a description of LC-LEP measurements that are required by the LC physics program, as well as critical instrumentation that is needed for realizing the LC luminosity goals.

The long pulse polarized beam to End Station A reflects many of the beam characteristics for the NLC beam at a 500-GeV collider. We have described how the existing beam and beam diagnostics can be utilized for LC-LEP beam tests.

We have presented an overview of LC-LEP beam tests that can be carried out at SLAC’s ESA to demonstrate the stringent requirements for the detectors and techniques to be employed at the Linear Collider. There is much work to do to carefully design meaningful and cost-effective beam tests. We can be ready for first beam tests in FY05.