

# STATUS REPORT

## A Demonstration of the Electronic and Mechanical Stability of a BPM-Based Energy Spectrometer for the International Linear Collider

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### Project Overview

This proposal seeks to demonstrate that a BPM-based Energy Spectrometer can be built which is both compatible with the ILC accelerator and can meet the energy measurement requirements driven by the ILC physics program.

Much of the physics of the future  $e^+e^-$  Linear Collider will depend on a precise measurement of the center-of-mass energy ( $E_{\text{CM}}$ ), the differential dependence of luminosity on energy ( $d\mathcal{L}/dE$ ), and the relationship between these two quantities and the energy of a single beam ( $E_{\text{beam}}$ ). Studies estimating the precision of future measurements of the top mass[1] and the higgs mass[2] indicate that a measurement of the absolute beam energy scale of 50 MeV for a 250 GeV beam ( $\delta E_{\text{beam}}/E_{\text{beam}} \sim 1 - 2 \times 10^{-4}$ ) will be necessary to avoid dominating the statistical and systematic errors on these masses. If precision electroweak measurements become necessary, the requirements on the beam energy measurement are even more stringent. Studies of a scan of the  $WW$  pair production threshold[3] have shown that an experimental error of 6 MeV may be possible, implying a needed precision of  $\delta E_{\text{beam}}/E_{\text{beam}} \sim 3 \times 10^{-5}$  (and likely an alteration in accelerator parameters to control  $d\mathcal{L}/dE$ ). Provisions must be made in the overall accelerator design to provide adequate beamline space for the devices which will

provide these energy measurements. Moving accelerator components well after construction in order to provide additional space for energy measurement instrumentation is likely to be both extremely disruptive and extremely expensive. We are in a situation, however, where no direct energy measurement technique except resonant depolarization (RDP)[4] has provided an energy determination of sufficient precision. Since RDP will not work in a single-pass collider, spectrometer techniques must be developed which meet the specifications demanded by physics measurements.

Previous experimental requirements on precision energy measurements at electron-based accelerators have led to the development of several techniques. At Jefferson Lab, wire scanners, etc.[5] have been used to provide a precision of  $\delta E_{\text{beam}}/E_{\text{beam}} \sim 1 \times 10^{-4}$  at beam energies of about 4 GeV. At higher energies, dedicated magnetic spectrometers have been constructed. At the SLC, the WISRD (Wire Imaging Synchrotron Radiation Detector)[6] was used to measure the distance between two synchrotron stripes created by vertical bend magnets which surrounded a precisely-measured dipole that provided a horizontal bend proportional to the beam energy ( $\sim 45$  GeV). This device reached a precision of  $\delta E_{\text{beam}}/E_{\text{beam}} \sim 2 \times 10^{-4}$ , where the limiting systematic errors were due to the relative alignment between the three dipole magnets and background issues associated with measuring the precise centroids of the synchrotron stripes. At LEP2, a magnetic spectrometer was incorporated into the LEP ring[7]. A precise map of the magnetic field at a series of excitations allowed a comparison of the nearly-constant bend angle across a range of LEP beam energies[8]. Since a precise calibration using RDP at the  $Z^0$  pole was possible, the spectrometer provided a relative energy measurement between this lower point and physics energies ( $\sim 100$  GeV). In this case, standard LEP Beam Position Monitors (BPMs) fitted with custom electronics were used to provide the angle measurement. This spectrometer has provided an energy determination at LEP2 energies of  $\delta E_{\text{beam}}/E_{\text{beam}} \sim 2 \times 10^{-4}$ , where the dominant errors have come from the stability of the BPM electronics.

As can be seen from the above results, ILC physics may require between a factor of 5 and 10 more precise energy determination than has been achieved with existing techniques. Bridging this gap is an essentially-technical challenge, where clever engineering solutions to the problems of nanometer-scale stability and resolution will be necessary. We need to develop a prototype support and position-monitoring system for the “magnetic spectrometer” option for Energy measurement, and, coupled with RF-BPM development at LBL and SLAC, a prototype BPM-based energy spectrometer which can demonstrate the required accuracy and stability in an electron beam test. The end goal of the proposal is the design of a magnetic-spectrometer-based Energy Measurement system for the ILC which can reach the desired precision. The “magnetic spectrometer” option is chosen as the focus primarily because it may be the only technique capable of achieving this goal in a position upstream of the Interaction Region, where manipulation of the beam phase space is very restricted.

The need for tests of this nature is becoming critical as the Global Design Effort progresses, since it directly impacts the design of the ILC Beam Delivery System. As elaborated below, the allowed emittance growth in the chicane is a primary design parameter and requires

design iteration with the optics experts currently laying out the accelerator components in this crucial region of the machine. The constraints provided by the available space and the limits on modifications of the beam parameters drive the stability and resolution requirements of the spectrometer components. However, if tests show that these tolerances are not feasible, the accelerator insertion will need to be redesigned. Test beam plans for the near future are discussed below.

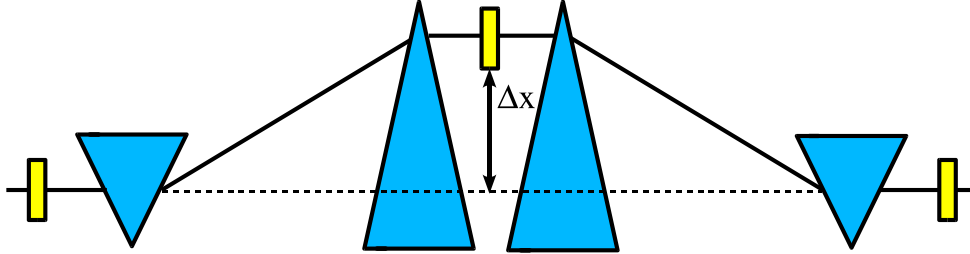


Figure 1: A schematic outline of an accelerator dipole chicane which could accommodate a BPM-based magnetic spectrometer at a future linear collider. The yellow rectangles denote possible BPM locations.

### *Energy Spectrometer Overview*

As summarized in Figure 1, a magnetic spectrometer at the LC will consist of a chicane of dipoles which deflect the beam for an energy measurement and return it to the lattice. In order to make an absolute, stand-alone energy measurement, the main dipoles will need to be turned “off”, in the situation shown at the center of Figure 1. Once the central BPM or BPMs measure a straight line, the dipoles can be re-energized, and the deflection relative to the initial straight line can be measured, determining the energy. Cycling the magnets between negative and positive polarities (“dithering”), as shown in Figure 2 below, cancels several systematic errors, especially that due to residual magnetic fields for the “straight line” measurement. Comparisons between the straight-line and “dithered” measurements will also be necessary to determine some systematic errors. To avoid hysteresis effects during operation, it is most likely that these dipoles should be super-conducting rather than typical iron dipoles. The BPMs external to the chicane are necessary to measure the incoming position and angle of the beam.

In order to make the energy measurement, the BPM response/gain/calibration must be stable over the time it takes to move the BPM or BPMs between the extrema of their excursions; the position of each of the BPMs relative to the inertial straight line must be known with sufficient accuracy and stability; and the BPMs must be able to be moved repeatedly and accurately over length scales of order 1cm with a precision of tens of nanometers. This proposal seeks to demonstrate the feasibility of each of these conditions in the context of deriving an overall design for a BPM-based spectrometer that is consistent with the ILC Beam Delivery lattice.

Prototyping the Mechanical Stability of a BPM-based Energy Spectrometer breaks down into

three natural stages:

1. establishment of a reference “straight line” optical or mechanical system to serve as the reference line for the energy measurement; demonstration of its stability, sensitivity to motion, and transverse measurement accuracy
2. design, fabrication, and testing of mechanical support structures and BPM movers to ascertain their short- and long-term stability
3. addition of a BPM triplet or quadruplet to measure beam position, resolution, and stability of position in a beam test. A dipole can then be added to prototype a full spectrometer system.

## **Status Report**

Substantial progress has been made on this project, driven by the urgency of the technology demonstration and the need to interface with other R&D efforts, such as the nano-BPM test program at ATF[9]. All of the proposed FY05 project deliverables have been achieved.

### *SLAC End Station A Test Beam*

In June 2004 a proposal for a test beam experiment at SLAC’s End Station A was submitted, with myself as spokesperson[10]. This program, designated T-474, is intended to provide the opportunity for a complete test of a BPM-based spectrometer system in a multi-year series of short experiments, and is part of a larger test-beam program at End Station A[11]. It has as collaborators groups from SLAC, LBL, University College London, and Cambridge University. This program has now been approved by SLAC; first beam is expected early in January 2006, with one or possibly two more running periods during 2006. The initial program will include electronic stability tests of cavity BPMs that were moved from the front end of the SLAC linac, looking at single and multi-bunch resolution issues with the expected ILC bunch spacing. Preliminary measurements were conducted in Summer 2005 of the mechanical stability of the beamline area using seismometers, and of the remnant magnetic fields using fluxgates. These data showed no pressing concerns for the use of the End Station for our experiments beyond what was expected given the human activity at the site. The steel spectrometer rails in the End Station do have a significant remnant field, but this should not impact the proposed tests using refurbished SPEAR electromagnets.

Subsequent years will see the measurement of the mechanical and electrical stability and their impact on the ultimate energy resolution of the spectrometer, and a test of the entire energy measurement system.

### *Optics Design*

The exact details of the accelerator optics around the spectrometer have yet to be determined (see FY2006 deliverables), and, as discussed above, will ultimately depend on the achievable stability and resolution. Our preliminary zero-th order design is shown in Figure 2. Features of this design are lengthened bends at the high dispersion point in order to minimize the emittance growth due to the emission of synchrotron radiation and an increase in the overall

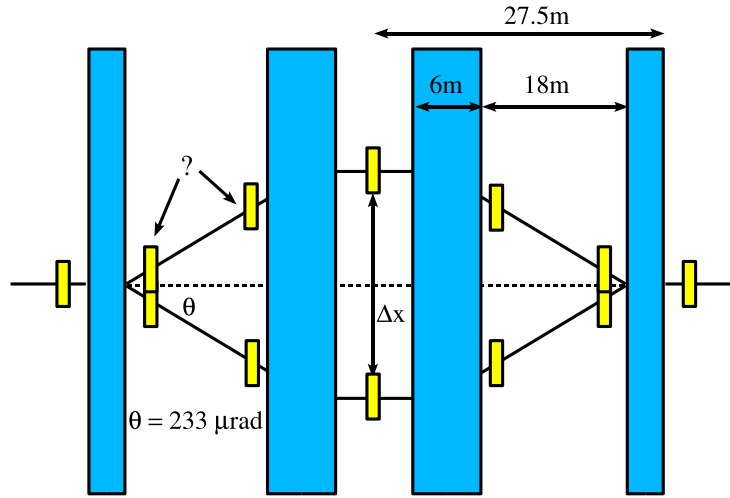


Figure 2: An example of an Energy Spectrometer chicane with a central dispersion of 5mm and a bend angle of  $233 \mu\text{rad}$ . The length of this chicane is approximately 55 meters. This version, with longer initial and final dipoles, has been integrated into the ILC lattice.

length of the chicane to achieve more position deviation at the central point. This design relaxes some of the constraints on the position measurement at the center of the chicane while minimizing the emittance growth due to synchrotron radiation at high-dispersion points in the lattice. The question mark on the diagram refers to the possibility of adding extra BPMs to over-constrain the beam position measurement. Redundancy was an important part of the LEP spectrometer design which turned out to be crucial in the final energy analysis[7]. This remains to be optimized.

This preliminary version of the design has been incorporated by Mark Woodley at SLAC into the ILC Beam Delivery lattice, as shown in Figure 3.

#### *Interferometric Position Monitoring*

At Notre Dame, I have taken delivery of a ZYGO 4004-based interferometer system, originally purchased by SLAC for the ATF nano-BPM effort. I have been evaluating its potential usefulness as a device to monitor the local position of a BPM-like mass. Some stability data is shown in Figure 4. These data were taken with the interferometer on a standard optical table in air, with no attempt to control temperature, air pressure, or humidity. This demonstrates the suitability of this optical system for single-axis position monitoring, even in stable air. Even higher resolution (and stability) would be possible by isolating the optical path in a low-grade vacuum system.

The current plan is to use this interferometer in beam tests at End Station A during the summer of 2006 to monitor the position and mechanical stability of a single BPM. Preliminary mechanical design work has begun on mounting fixtures, etc., in order to enable several interferometer heads to observe a single BPM girder. Work has also begun on conceptual

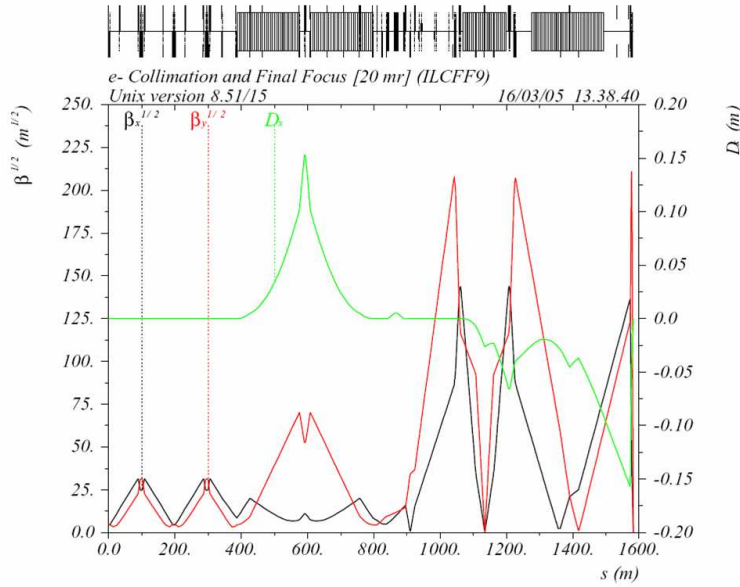


Figure 3: An overview of the twiss parameters for a 2005 version of the ILC Beam Delivery System. The collimation system lies at the center of the left figure and the IP at the right; the Energy Spectrometer is around the 900 meter mark, where the 5mm dispersion at the center of the spectrometer chicane can be seen as a small bump in  $\eta_x$ . The total length of the spectrometer insert here is approximately 54 meters, a distance specified to correspond to our zero-th order design, shown in the previous figure. Our specifications for magnet lengths and bend strengths have also been included. The baseline design now includes energy spectrometers of this type in all incoming beam lines to the IPs.

designs of a straightness monitor which may also be tested this summer. Discussions have also begun with the Oxford LiCas[13] group, who are very interested in developing a straightness monitor with nanometer resolution over distances approaching 1 meter transversely.

**FY2006 Project Activities and Deliverables** The second year of the project will produce a prototype local position readback system for testing in the End Station A beamline. Prototype designs for the overall “straightness monitor” will also be developed. The aim of the End Station A tests in FY2006 will be to demonstrate electric and mechanical stability in the beam at the  $10^{-4}$  level. Procedures for measuring and monitoring the BPM gains will be developed.

**FY2007 Project Activities and Deliverables** FY2007 will see the installation of a dipole in the End Station A line for a prototype energy measurement. The straightness monitor, in whatever form it takes, will be installed. A  $10^{-4}$  energy measurement will be made, and compared to the synchrotron light spectrometer in the same beamline. Studies of BPM scanning procedures will be made.

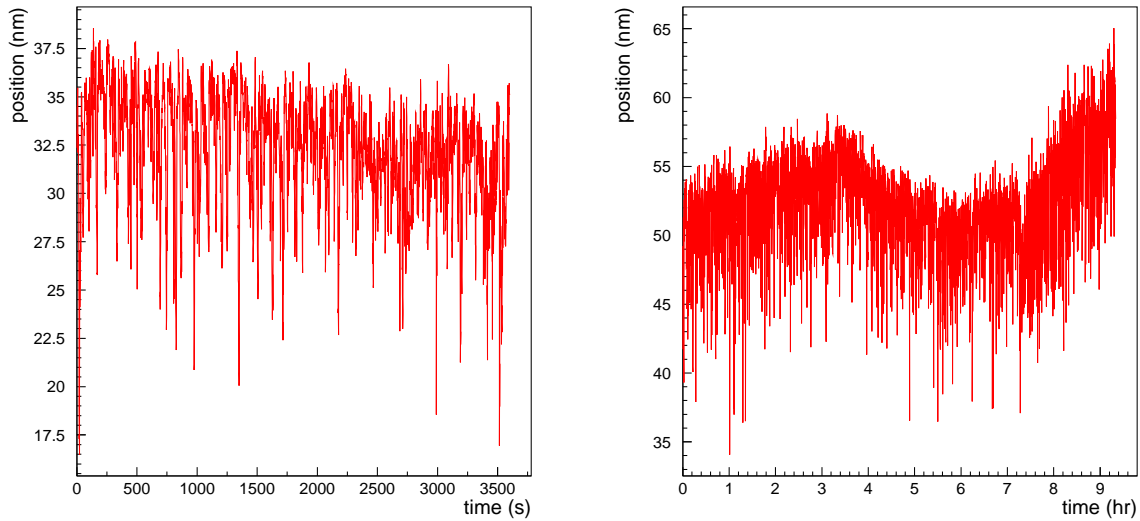


Figure 4: Single-axis position stability using a Zygo 4004-based interferometer. Left: Data taken at 1 Hz for an hour, showing a slow drift of order 5nm and an rms jitter of approximately 3nm. Right: Data taken at 0.1 Hz for 9 hours. Similar stability is seen, even though there is no atmospheric control in the lab room.

**Two-year budget, in then-year K\$**

**Institution: University of Notre Dame**

Item	FY2006	FY2007	Total
Other Professionals	30	32	62
Graduate Students	22	24	46
Undergraduate Students	3	4	7
Total Salaries and Wages	55	60	115
Fringe Benefits	6.4	6.9	13.3
Total Salaries, Wages and Fringe Benefits	61.4	66.85	128.25
Equipment	30	30	60
Travel	4	4	8
Materials and Supplies	5	5	10
Other direct costs	0	0	0
Total direct costs	100.4	105.9	206.3
Indirect costs	35.2	37.9	73.1
Total direct and indirect costs	135.6	143.8	279.4

**Budget justification:** Travel funds sufficient for visiting SLAC are included in all years.

The second year will involve mechanical design and fabrication of the straightness monitor prototype and the local position readback system. Costs for engineering (1/3 FTE) and fabrication are included. Manpower for mounting this effort will come from an undergraduate student and a full-time graduate student as well as staff (not included).

This level of staffing continues in the third year, as more components for the position monitoring will be needed for the final spectrometer test. As the construction progresses to a final position measurement system, more and more of the equipment funds are capital equipment, hence the lower indirect costs.

Fringe is assumed 20% on salary; the indirect cost rate at Notre Dame is 50%.

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