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

Classification (subsystem)

Machine-Detector Interface

Personnel and Institution(s) requesting funding

Michael D. Hildreth, University of Notre Dame

Collaborators

Yury Kolomensky, Lawrence Berkeley National Laboratory and University of California, Berkeley

Ray Arnold, Joe Frisch, Marc Ross, Peter Tenenbaum, Mike Woods, Stanford Linear Accelerator Center

David Miller, Alex Ljapine, University College London

David Ward, Mark Thomson, Cambridge University

Project Leader

Michael Hildreth
mikeh@undhep.hep.nd.edu
(574) 631-6458

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_{CM}), the differential dependence of luminosity on energy ($\mathrm{d}\mathcal{L}/\mathrm{d}E$), and the relationship between these two quantities and the energy of a single beam (E_{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 ($\delta E_{\mathrm{beam}}/E_{\mathrm{beam}} \sim 1-2\times10^{-4}$) 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 $\delta E_{\mathrm{beam}}/E_{\mathrm{beam}} \sim 3\times10^{-5}$ (and likely an alteration in accelerator parameters to control $\mathrm{d}\mathcal{L}/\mathrm{d}E$). 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 $\delta E_{\rm beam}/E_{\rm beam} \sim 1 \times 10^{-4}$ 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 $\delta E_{\rm beam}/E_{\rm beam} \sim 2 \times 10^{-4}$, 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 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 $\delta E_{\rm beam}/E_{\rm beam} \sim 2 \times 10^{-4}$, 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.

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

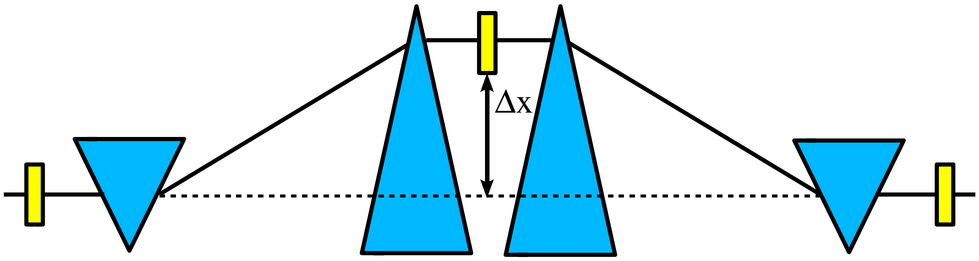

Figure 1: A schematic outline of an accelerator dipole chicane which could accommodate a BPM-based magnetic spectrometer at a future linear collider. The yellow rectangles denote possible BPM locations.

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 3 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.

Before presenting the proposed future research, a review of recent progress is necessary.

Results of Prior Research

Although no funding has been allotted to this effort, the project has made substantial progress.

This has been 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].

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 envisioned 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 sometime in early FY06. 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 337 or 168 ns bunch spacing. Some preliminary tests of mechanical stability are also envisioned for this year, pending results of STS-2 seismometer[12] studies scheduled for summer. 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. Monetary support for this effort is necessary if I am to continue working on this program.

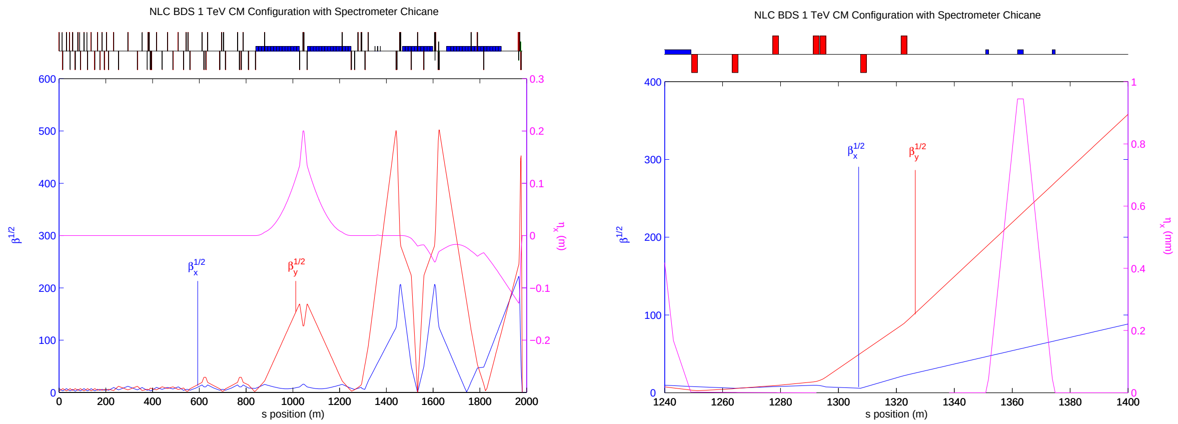

Figure 2: Left: An overview of the twiss parameters for a 2004 version of the NLC Beam Delivery System, which is very similar to the forthcoming ILC one. The collimation system lies at the center of the left figure and the IP at the right; the Energy Spectrometer is around the 1360 meter mark. Right: A closer view of the Spectrometer region. The total length of the spectrometer insert here is approximately 37 meters. The large increase in dispersion here is a small bump on the left plot, with a maximum of 1mm. This set of optics will be modified in the final design to make the beta functions more symmetric in the Spectrometer region and to provide larger dispersion.

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 am in the process of evaluating its potential usefulness as a device to monitor the local position of a BPM-like mass. By summer, I expect to have some results and a preliminary design for a “local” optical monitoring system for a single BPM for use in the End Station A beamline.

Discussions have also begun with the Oxford LiCas[13] group, who are very interested in

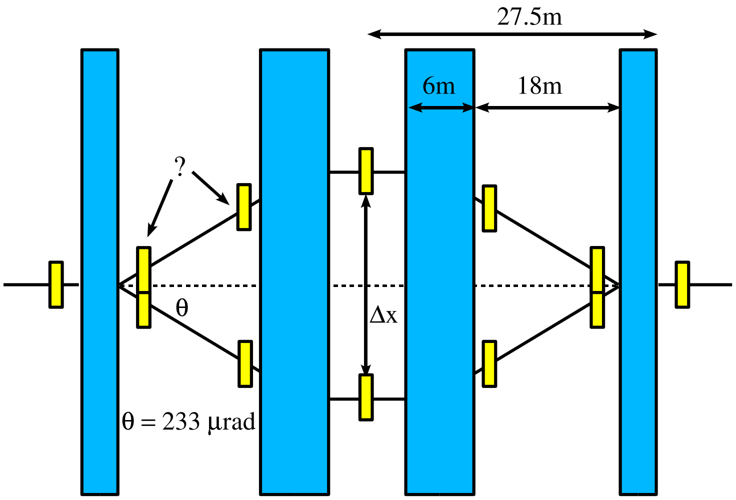

Figure 3: An example of an Energy Spectrometer chicane with a central dispersion of 5mm and a bend angle of 233 μrad. The length of this chicane is approximately 55 meters. This version, with longer initial and final dipoles, is being integrated into the ILC lattice.

developing a straightness monitor with nanometer resolution over distances approaching 1 meter transversely.

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. A preliminary chicane has be designed by Peter Tennenbaum which will allow the straight-ahead and deflected beams to pass through to the rest of the accelerator with an acceptable emittance growth. The details are shown in Figure 2. As designed, this chicane requires sub-100nm total BPM resolution and stability, which may be too stringent. We have recently attempted to optimize this design further to relax the constraints on the position measurement. An example of this is shown in Figure 3, where we have lengthened the bends at the high dispersion point in order to minimize the emittance growth due to the emission of synchrotron radiation and have changed the overall length of the chicane to achieve more position deviation at the central point. A modified version of this example is being implemented in the Beam Delivery System of the new ILC 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.

Proposed Research

This proposal seeks to continue the line of research begun over the past two years until a design for the BPM-based spectrometer exists whose parameters have been justified by test beam data.

This work will include an iterative design procedure which takes into account the constraints imposed by the parameters of the incoming beam and the induced emittance growth. Challenges are posed by external parameters, such as incoming beam current, position and angle jitter, residual magnetic fields, and measuring and monitoring the integrated bend field in all four dipoles. These effects will be confronted with the available, measured mechanical stability and the measured electronic stability and resolution of the BPMs. Only then can a robust spectrometer with sufficient resolution be designed.

While the overriding concern of this proposal is the ultimate proof-of-principle and design of the spectrometer itself, the specific focus of the Notre Dame effort is mechanical stability and monitoring the positions of the beamline components. The establishment of an “straight” line reference is most easily achieved optically in this case with a laser interferometer, which can be set up under vacuum to minimize thermal effects. Monitoring of the relative positions of the BPMs and the optical elements themselves can be achieved using the same techniques that have been developed for the stabilization of the LC Final Focus quadrupoles at SLAC and at the University of British Columbia[14] or the LiCas project[13]. We hope to benefit by close collaboration with these groups. Local position measurements of the BPMs, from either optical encoders or interferometric systems, will also be necessary, and we will pursue a suitable solution to this problem as our first priority. Sensitivity tests in our lab at this stage will require piezo movers of known calibration, and perhaps a capacitive position encoder. Seismometers such as the STS-2[12] will also be tested for long-term stability.

For the geometry shown in Figures 1 and 3, the required BPM resolution and stability of measurement is roughly 100-200 nm. Since RF-BPMs with a resolution of 25 nm[15] have been used at the Final Focus Test Beam at SLAC and at the ATF, the necessary performance in terms of pure resolution has been achieved. Stability over the measurement time, however, has yet to be demonstrated. Development at LBL/Berkeley and SLAC will focus on these issues, as they will provide the RF BPM components which complement the mechanical systems outlined here. Ample tests of these parameters will be made at SLAC and at ATF over the coming years. The tantalizing possibility exists that the BPM resolution will be good enough to make a relative energy measurement along the bunch train for the full ILC bunch with energy resolution much better than the average energy spread.

A crucial item for this project is the BPM movers. Designers for the magnet support structures are currently considering a modified version of the FFTB magnet movers[16] to support the magnetic elements in the Beam Delivery System. These are robust cam-driven movers capable of positioning with little backlash at a precision of 0.3 μm. A re-design of these movers should be possible to yield a mover with better precision and the longer travel distance required for our applications. SLAC designers will act as consultants on the support stand design and fabrication.

As detailed above, these systems will be subject to repeated testing in the End Station A beam. Verification of position resolution and stability in a real beamline is essential for the success of the spectrometer. Many beam-induced effects are possible (and were experienced in building the LEP Spectrometer), such that significant beam test time will be necessary in order to iterate on the electronic or mechanical systems if needed. Only then can one arrive at a final design with sufficient performance. As well as contributing invaluable ideas and insights throughout the process, our SLAC collaborators will provide logistical support and coordination for the final stage of the project when beam tests occur, as is specified in the test beam proposal.

Broader Impact

This project provides an ideal opportunity for students, particularly undergraduates, to gain hand-on experience working on cutting-edge research. Already, two undergraduates are working in our lab at Notre Dame setting up the interferometer system, writing the VME data-acquisition code, and performing stability tests. The project requests support for summer stipends for undergraduates to spend time at SLAC working on setting up the test beam equipment and evaluating hardware, such as the seismometers.

The collaboration formed for this enterprise includes several groups from Europe who will bring talented students, postdocs, and engineers into the project. This bolsters not only the project itself but the real international partnerships that have formed to carry out the ILC design and construction.

Facilities, Equipment and Other Resources This project will have access to SLAC End Station A, with ancillary infrastructure provided by SLAC. This includes computing, data acquisition, rigging, electricity, etc. Our lab at Notre Dame includes a VME-based test station and an optical table and components for interferometry tests.

FY2005 Project Activities and Deliverables In 2005 initial tests will begin to determine appropriate methods of measuring the mechanical stability of the BPMs. Seismometers, interferometers, and other encoder methods will be studied. Development of appropriate movers for the BPM positioning will begin. In parallel, an investigation of the potential locations of such a device in the accelerator lattice will be explored. The first deliverable is a conceptual design of an appropriate way to monitor the local position and tilt of a BPM to sub-100nm precision over long time scales. The second deliverable is a conceptual spectrometer design with an optics deck for the ILC design including the spectrometer chicane. This prototype design should meet all accelerator constraints and should easily reach the design goal of 10^{-4} energy precision subject to the expected stability and resolution.

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.

Budget justification: The first year’s experiments involve setting up the optical interferometer system and making some simple measurements. This will be accomplished by staff members (not included here) with the help of an undergraduate. Sufficient equipment and supply funds are included in order to purchase a vacuum system in which to run the interferometer, and piezo movers for testing. 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.

Three-year budget, in then-year K$

Institution: University of Notre Dame

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	30	32	62
Graduate Students	0	22	24	46
Undergraduate Students	3	3	4	10
Total Salaries and Wages	3	55	60	118
Fringe Benefits	0	6	6.4	12.4
Total Salaries, Wages and Fringe Benefits	3	61	66.4	130.4
Equipment	10	30	30	70
Travel	4	4	4	12
Materials and Supplies	6	5	5	16
Other direct costs	0	0	0	0
Total direct costs	23	100	105.4	228.4
Indirect costs	5	33.5	35.7	74.2
Total direct and indirect costs	28	133.5	141.1	302.6

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