PRECISION MEASUREMENTS OF THE SLC BEAM ENERGY*

J. KENT, M. KING, C. VON ZANTHIER, S. WATSON
University of California at Santa Cruz, Santa Cruz, California 95064

M. LEVI, F. ROUSE
Lawrence Berkeley Laboratory, Berkeley, California 94720

P. BAMBADE†, R. ERICKSON, C. K. JUNG, J. NASH, G. WORMSER†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

ABSTRACT

A method of precisely determining the beam energy in high energy linear colliders has been developed using dipole spectrometers and synchrotron radiation detectors. Beam lines implementing this method have been installed on the Stanford Linear Collider. An absolute energy measurement with an accuracy of better than $\delta E/E = 5\times10^{-4}$ can be achieved on a pulse-to-pulse basis. The operation of this system will be described.

1. INTRODUCTION

The physics program of the Stanford Linear Collider (SLC) requires precise measurements of the center-of-mass energy.[1] The goal is to determine center-of-mass energies to an absolute accuracy of $\delta E/E = 5 \times 10^{-4}$. To achieve this goal, spectrometers have been designed and installed in both the electron and positron extraction lines. These spectrometers are now operational.

The SLC required the development of a novel approach to the measurement of absolute beam energies. Techniques used at storage rings often make use of the closed beam orbits and hence cannot be applied to linear colliders. Energy spectrometers installed in the extraction lines of the SLC satisfy the need for precise energy determinations. The method of measurement is to indirectly observe the deflection of charged beams via the narrow beams of synchrotron radiation they emit.

2. DESCRIPTIOIN OF THE SLC EXTRACTION-LINE SPECTROMETERS

Figure 1 shows schematically the design of the energy spectrometers installed in the extraction lines of the SLC. Approximately 150 m downstream of the interaction point, both the electron and positron beams pass through extraction-line spectrometers before reaching their beam dumps. In each spectrometer, the $e^{\pm}$ bunch travels through a string of three dipole magnets (B31, B32, and B33). Magnet B32 is a well-measured spectrometer magnet (set at $\int Bdl = 3.05\ T \cdot m$ when E_{beam} is 50 GeV) which bends the beam by an amount proportional to $\int Bdl/E_{beam}$. Magnets B31 and B33 bend the beam perpendicular to the bend direction of B32 and cause the beam to emit two swaths of synchrotron radiation. Quadrupole magnets upstream of the bending magnets focus the $e^{\pm}$ and synchrotron swaths approximately 15 m downstream of the spectrometer magnet. Synchrotron radiation detectors located at this focal point measure the distance between these swaths (approximately 27 cm) and thus the angle through which the beam has been bent by magnet B32. Combining this information with the strength of the magnet allows a determination of the energy of the beam. Analysis of the widths of the synchrotron stripes yields the energy spread of the beam.

To achieve absolute determinations of beam energies to the desired level, the separation between the swaths of synchrotron radiation must be measured absolutely with high precision. In this regard, the use of synchrotron radiation provides two decisive advantages over spectrometer designs based on direct measurements of $e^{\pm}$ beam positions. First, it is easier to make precise absolute measurements of the synchrotron swath positions than of primary $e^{\pm}$ beam positions. If a monitor for an intense charged-particle beam does not involve placing material in the path of the beam, it tends to have problems with absolute position calibration. Monitors intercepting the beam with material tend to disrupt the beam and thus have problems if beam position measurements at several locations are needed simultaneously. Second, survey and alignment are considerably easier for a pair of synchrotron radiation detectors separated by 27 cm than for a sequence of $e^{\pm}$ beam position monitors distributed along tens of meters of beam line.

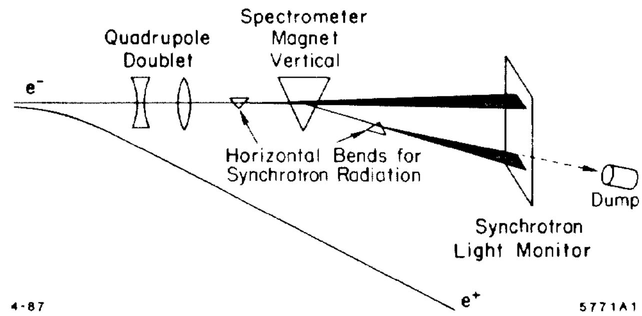

Fig. 1. Conceptual design of the extraction-line spectrometers.

Special care has been given to the determination of the field strength of the analyzing bends. The bending strengths of the analyzing bends are known absolutely within an error of 0.01%. Two high precision, absolute methods were used to make a determination of the magnetic strength of the spectrometer magnets prior to their installation in the extraction lines. The first method measured $\int Bdl$ directly by moving NMR probes along the length of the magnet, measuring B and dl for each step. In the second method, $\int Bdl$ was measured by monitoring the voltage induced on a moving loop of wire. Agreement between these two techniques give us confidence in our measurements. These absolute measurements were used to simultaneously calibrate three online methods of determining the spectrometer strengths: a flip coil, NMR probes, and current monitors. The on-line field strength measurements from the flip coil and the NMR probes provide redundant information at the desired level of precision. These magnetic measurements are described in more detail elsewhere.[2]

Two independent detector systems have been designed and installed for the purpose of monitoring the separation of the swaths of synchrotron radiation. One system making use of phosphorescent screens is now successfully in operation. A second system based on ejection of Compton recoil electrons from arrays of fine wires is nearing completion. These systems are briefly described below and discussed in more detail elsewhere.[3]

The phosphorescent screen monitors consist of two identical target and camera systems to monitor both stripes simultaneously. An Invar (iron-nickel alloy with low thermal expansion coefficient) support structure holds both targets and fixes the

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† Present address LAL-Orsay, 91405 France.

distance between them. Each target consists of an array of 100 μm diameter fiducial wires with center-to-center spacing of 500 μm and a phosphorescent screen which emits light where struck by the synchrotron beam. The individual wires and the spacing between the two arrays were measured on precision optical comparators. A camera system records both the fiducial wires and the synchrotron stripe which runs parallel to them. The video frame is digitized and compressed by a DSP Technology 2030/4101 signal averager into a one-dimensional array (perpendicular to the wire direction) before readout. Readout rates up to the SLC design repetition rate (180 Hz) are possible.

In the second detector system—the wire imaging synchrotron radiation detectors—there are again two targets held in position by an Invar support structure. Here the targets consist of arrays of 75 μm diameter copper wires spaced 100 μm apart (center-to-center). The wires are held in place in a ceramic card which is glued to the support structure. Incident synchrotron radiation ejects electrons from the wires via Compton scattering. The residual charge (calculated to be typically 200 fC with $10^{10}e^{\pm}$ in the primary beam bunch) is sampled by a charge sensitive preamplifier (LeCroy HQV820), then amplified, shaped, and digitized. The electronics are designed for readout rates up to 180 Hz.

Both of these detector systems are designed to measure absolutely the separation of the synchrotron stripes to better than 0.02%. This goal has been achieved with the phosphorescent screen monitors.[3] When data from the wire imaging synchrotron radiation detectors becomes available, there will be redundant precision measurements of the absolute separation of the synchrotron stripes.

Measurements of the energy of both beams were performed during the 1988 SLC run.[4] Figure 2 shows the energy of the electron and positron beams as measured by the energy spectrometer for a sample of 100 consecutive triggers of the Mark II detector. This data was taken during a period in which the beams were stable. Attributing the fluctuations to the spectrometer measurements and not the beams themselves, we estimate the short term relative pulse-to-pulse energy resolution for both the positron and the electron spectrometers to be approximately 5 MeV.

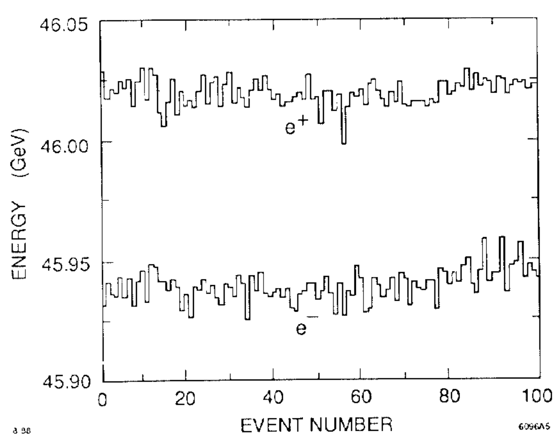

Fig. 2. Energy measured vs. Event Record Number

3. DISCUSSION OF SYSTEMATIC ERRORS

The goal of measuring the center-of-mass energy to an absolute accuracy better than $\delta E/E = 5 \times 10^{-4}$ now appears within reach. Below we calculate the overall systematic error we expect to achieve in the determination of center-of-mass energies. First we consider the error in the energy measurement for a single beam.

The dominant systematic errors anticipated in the absolute determination of the energy of each beam are presented in Table 1. The numbers quoted are errors for a single 50 GeV beam. The magnetic measurement error of ±0.01% includes errors from both the absolute field mapping and the online monitoring of the field. Here we assign an error of 0.02% to the measurements of the separation between the pairs of synchrotron stripes. We anticipate redundant measurements at this level in the near future. The phosphorescent screen monitor already provides measurements at this level of precision. The next entry in Table 1 refers to rolls of the dipole magnets with respect to their desired orientations, that is, the degree to which we can assume that the detected swaths are perpendicular to the direction of the analyzing bend. This effect was studied by simultaneously measuring the positions of stripes at two different locations on the phosphor screens. The error quoted is for a measured misalignment of 2 mrad. This is a conservative error estimate since corrections can be applied. Survey data is available with which to determine the distance from the magnetic center of the spectrometer to the phosphor screens within an accuracy of 1.5 mm. Further redundant measurements of this distance will be made to assure that this distance is reliably known. In summary, the spectrometers will provide absolute measurements of beam energies within a total systematic error of 20 MeV.

Table 1. Systematic Errors

Source of Error	Size of Error
Magnetic measurement	5 MeV
Detector position resolution	10 MeV
Rotational errors in magnet alignment	16 MeV
Survey errors	5 MeV
Total Error	20 MeV

The average energies of the electron and positron beams do not in themselves completely determine the center-of-mass energy for the collider. The beam conditions at the interaction point can influence the luminosity-weighted center-of-mass energy. The dominant effect is expected to be due to residual momentum dispersion (nominally zero) at the point of collision. If there is an offset between the electron and positron beams, residual dispersion in one of the beams will shift the luminosity-weighted center-of-mass energy. This effect has been estimated[1] to contribute 30 MeV to the systematic error in the center-of-mass energy. A more refined estimate of this source of error will be forthcoming as more is learned about the operation of the SLC. Combining this estimated error with the errors from each individual beam gives an expected absolute error on the center-of-mass energy of 40 MeV. This implies that the design goal of $\delta E/E < 5 \times 10^{-4}$ will be achieved.

In order to determine the impact of systematic errors on the ability of the SLC to measure the mass and width of the Z^0, studies were done to determine the statistical errors on these measurements. Figure 3 shows the statistical error on the mass and width measurements as a function of integrated luminosity. These plots are for a scanning strategy in which equal luminosity is taken at five equally spaced energy settings. The systematic error on the mass includes the absolute systematic error for both beams added in quadrature and the systematic error for residual dispersion effects at the interaction point. The error on the width includes only relative systematic errors for each beam along with the dispersion error. The extraction-line spectrometers improve by an order of magnitude the absolute determinations of SLC energies; from the figure it is evident that the spectrometers significantly enhance the physics potential of the SLC program.

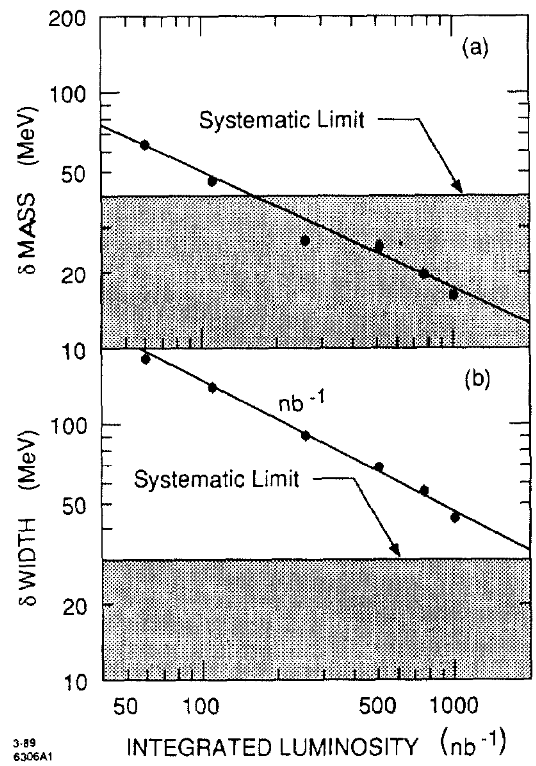

Fig. 3. Statistical errors in measuring the mass and width of the Z^0.

4. CONCLUSION

The SLC physics program requires precise absolute measurements of beam energies. Novel energy spectrometers developed for this purpose have been installed in the SLC extraction lines. The key idea is to observe the deflection of an $e^{\pm}$ beam by monitoring beams of synchrotron radiation generated before and after the analyzing bend. The spectrometers are now in operation.

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