Beam Energy Measurement at a Linear Collider with an SLC Style Energy Spectrometer

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Abstract. We discuss the energy measurement requirements for the physics program at a next generation linear collider. The SLC energy spectrometer and its performance are described. We conclude that there may be a use for a modification of this spectrometer in the extraction line, but that the primary energy measurement should be integrated into the accelerator. It will be difficult to achieve the accuracy desired for some of the physics objectives.

ENERGY MEASUREMENT REQUIREMENTS

We list in Table 1 likely requirements on the accuracy of the energy measurement for several physics topics. In addition to measuring an average energy, the physics requires knowledge of the luminosity spectrum to obtain luminosity-weighted energies, or to understand energy thresholds. The accuracy requirements for SUSY and top physics can be met a variety of ways. The requirements for Giga-Z physics and for the W mass measurement are the most demanding.

TABLE 1. Likely Physics Requirements on Beam Energy Measurement.

Physics	Requirement	E_{BEAM} Accuracy	Difficulty
SUSY Masses	0.1%	1400 ppm	Easy
SUSY Mass Ratios	0.1%	1000 ppm	Easy
Top Quark Mass (Ecm)	100 MeV	800 ppm	Easy
W Boson Mass (Ecm)	< 6 MeV	< 100 ppm	Difficult
0.1 Giga-Z Physics (Ecm)	10 MeV	160 ppm	OK
Giga-Z Physics w/Pe+	2–5 MeV	30–80ppm	OK?

For very high statistics (~10^9 events) running at the Z-pole with polarized positrons, or with high precision electron polarimetry, the center of mass energy should be known to better than 5 MeV. Since the current uncertainty in the Z mass is 2.2 MeV, this would be quite demanding as an absolute measurement. However, with high luminosity, one could periodically scan the Z peak for calibration, and the energy can probably be measured relative to the Z mass to better than 5 MeV.

The requirement for the W mass measurement is more challenging. The absolute accuracy of 100 ppm is difficult to achieve, but one might be able to return to the Z-pole for periodic calibration of a relative energy measurement. It is not clear if the energy can be varied by a factor of up to 4 without loosing the desired accuracy, or causing some other problem. This is potentially a serious problem for the W mass.

THE SLC/SLD ENERGY SPECTROMETER

A schematic of the SLC energy spectrometer is shown in Figure 1. There is a spectrometer in each SLC extraction line, just before the beam dump. Two bend magnets create horizontal stripes of synchrotron radiation with $k_c \approx 3$MeV. The vertical bend in the spectrometer magnet separates these stripes, and measurement of the separation determines the energy.

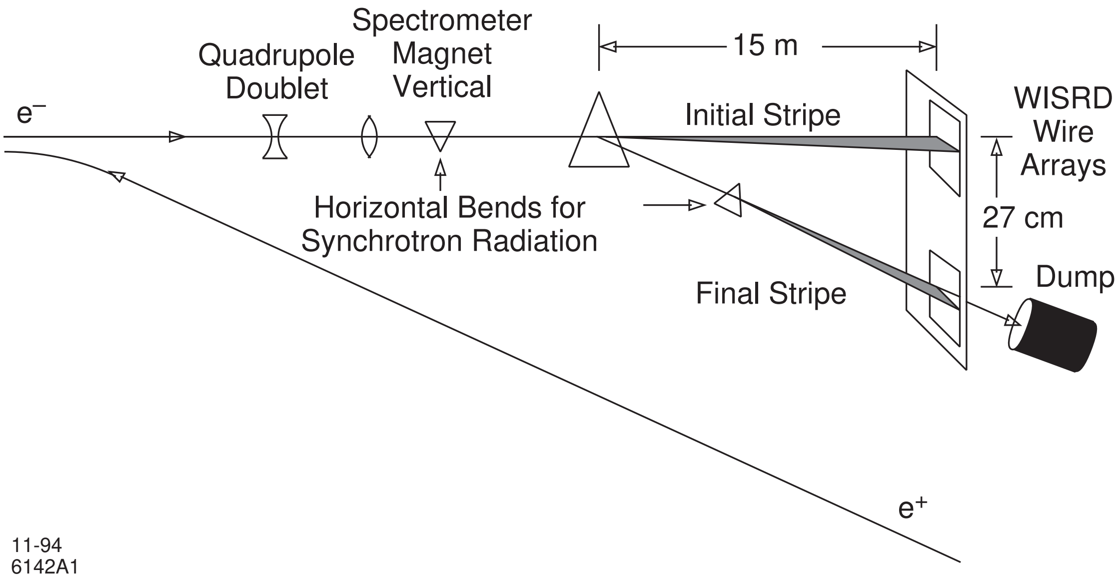

FIGURE 1. Schematic of the SLC/SLD extraction line energy spectrometer.

When the SLC energy spectrometer was used by the SLD experiment, the synchrotron radiation was incident on fine wire arrays, and the stripe positions were determined by measuring the charge ejected from the wires by the incident radiation. This system allowed measurements to be made at the 120 Hz beam pulse rate.[1]

The spectrometer magnetic field was continuously monitored with a rotating coil that extended the full length of the magnet. The uncertainty in the beam energy due to magnetic field measurement and monitoring was estimated to be 100 ppm (4.6 MeV).[2] Survey of the wire arrays contributed 90 ppm uncertainty, and survey of the magnet positions contributed 170 ppm, almost entirely from the relative rotation of the stripe-producing magnets. The total uncertainty due to these effects was 217 ppm. Calculations, including energy loss between the interaction point and spectrometer, contributed 135 ppm uncertainty, for a total of 255 ppm (12 MeV)[3] per beam.

Assuming that the effect of pulse-to-pulse electronic noise averaged to zero, and that the calculation uncertainties were correlated, the uncertainty in the center of mass energy was 288 ppm, or 26 MeV. In addition to the mean energy, the spectrometer also provided a measure of the beam energy spread, although it was not optimized for this purpose. By moving the beams out of collision, it was possible to measure the average energy loss due to the beam-beam interaction.

ACCURACY OF THE SLC ENERGY SPECTROMETER

Prior to 1998 the SLC luminosity was too low to consider a scan of the Z peak, and the SLC energy measurement relied on the original 1988 magnetic measurements[2] and periodic surveys of the magnet locations. The higher luminosity in 1998 allowed SLD to scan the Z peak, effectively calibrating the SLC spectrometer energy against the LEP energy scale.[4] The Z peak scan lead to the conclusion that the center of mass energy determined by the SLC spectrometer was low by 46 ± 25 MeV.

The colinearity of muon pairs measures the difference between the two beam energies, while the center of mass energy is their sum. Using the acolinearity of muon pairs recorded during the Z peak scan, we determined that the discrepancy in the energy scale was due to an offset of 46 ± 27 MeV in the positron spectrometer energy, and that the electron spectrometer energy offset was 0 ± 27 MeV.

A careful study was made of the original survey data for the wire arrays, and of the magnet position surveys for both spectrometers, but no errors that could cause such a large energy offset were found.

The original magnetic measurements revealed a noticeable non-uniformity in the positron spectrometer magnetic field.[2] Because the rotating coil monitors the average field continuously, minor variations in magnet current should have little impact on the reported beam energy. However, with a large field non-uniformity, it is important to always standardize the magnet by running it through several hysterisis cycles when first powered, and to control the beam orbit carefully. In the opinion of the author, too little attention was paid to these issues during operation, and this is the most likely origin of the energy scale discrepancy. A quantitative assessment has not been done.

APPLYING THE SLC EXPERIENCE TO FUTURE COLLIDERS

The SLC energy spectrometer provided stable pulse-by-pulse energy measurements during most of the SLD running. However, the stability and resolution of the energy measurement degraded in the highest luminosity running, presumably due to beamstrhalung incident on the wire arrays. If one wanted to use a similar spectrometer at a linear collider, other methods should be considered for detection of the SR stripes.

The large energy loss at a high energy linear collider has several implications for an extraction line energy spectrometer, in addition to the presence of beamstrahlung radiation. The energy measured will be an average over disrupted beam energies, not the nominal beam energy. Beam variations cause variations in the beamstrahlung, and the average measured energy will fluctuate. Stable measurements of the beam energy can be made if pulses are taken out of collision for this purpose. However this reduces integrated luminosity, probably requires sampling of the pulse trains, and may cause difficulty in maintaining stable beams at the interaction point.

Some of the difficulties encountered in the SLC energy spectrometer were because it was an add-on, designed after SLC construction. One consequence was the poor access for survey of magnet positions, in particular the roll angles of the stripe-producing magnets. Also, no provision was made for beam-based measurement of the relative magnet roll, the source of the largest single systematic error.

No provision was made for long term monitoring of the absolute calibration, nor for long term comparison with energy measurements in the SLC. For more than 10 years the energy measurement relied on the initial magnetic measurements, continuous monitoring of the rotating coil, and periodic survey of magnet positions.

CONCLUSIONS

Because of the beam-beam interaction a spectrometer in the extraction line is not well suited to precise measurement of the beam energy in a high energy linear collider. On the other hand, with appropriate beam optics, an extraction line spectrometer can measure the energy distribution of the beam after interaction. If such data were useful, in addition to that obtained from Bhabha events, this is would be the best use of an SLC style energy spectrometer in the extraction line.

At several locations in the SLC itself, the energy was measured with excellent long-term stability and resolution better than 20 ppm (1 MeV). (Because precision absolute magnetic measurements had not been made, these were considered relative energy measurements, used to maintain stable machine energy.) Thus, it seems that the best absolute energy measurement would be achieved if the measurement apparatus and precision magnets were integrated into the design and operation of the accelerator. There is some question of how well an absolute measurement can be made using beam position monitors, but the experience at LEP2 suggests that this can be done quite well with adequate planning and care in design and operation of the system.[5]

If the collider is to run at the Z pole with very high statistics ($\sim 10^9$ events) and precision polarimetry, the center of mass energy must be known to less than 5 MeV, which can probably be done by periodic calibration with a scan of the Z peak.

Measuring the W mass to < 6 MeV requires an energy measurement to < 100 ppm. The goal for the LEP2 energy spectrometer is a <u>relative</u> measurement of 100 ppm, and the error in the W mass due to the LEP2 energy scale is now 17 MeV.[5,6] If the energy measurement is to be calibrated against the Z mass, the machine energy will have to be varied a factor of up to 4 for each calibration, which would involve a number of new technical issues. The feasibility of the desired absolute or relative beam energy measurement for the W mass determination has not been clearly demonstrated.

Because the luminosity spectrum is important to all physics for which energy is critical, the use of Bhabhas or other physics events is a part of energy measurement. This was addressed in the ECFA/DESY physics and detector studies, and must be considered across working groups in all physics and detector design studies.

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