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POLARIZATION AT THE SLC*

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ABSTRACT

The Stanford Linear Collider was designed to accommodate polarized electron beams. Longitudinally polarized electrons colliding with unpolarized positrons at a center of mass energy near the Z^0 mass can be used as novel and sensitive probes of the electroweak process. A gallium arsenide based photon emission source will provide a beam of longitudinally polarized electrons of about 45 percent polarization. A system of bend magnets and a superconducting solenoid will be used to rotate the spins so that the polarization is preserved while the 1.21 GeV electrons are stored in the damping ring. Another set of bend magnets and two superconducting solenoids orient the spin vectors so that longitudinal polarization of the electrons is achieved at the collision point with the unpolarized positrons. A system to monitor the polarization based on Møller and Compton scattering will be used. Nearly all major components have been fabricated and tested. Subsystems of the source and polarimeters have been installed, and studies are in progress. The installation and commissioning of the entire system will take place during available machine shutdown periods as the commissioning of SLC progresses.

INTRODUCTION

The Stanford Linear Collider (SLC) at the Stanford Linear Accelerator Center is unique among existing or planned colliding beam facilities in its potential to accelerate longitudinally polarized electrons. The polarization sense is reversible from pulse to pulse at the operator's control, and thereby precise tests of the coupling of fermions through the measurement of the left-right asymmetry

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

can be made. Here σ_L (σ_R) is the cross section for left-handed (right-handed) electrons on unpolarized positrons. In the standard model A_{LR} is uniquely predicted once M_Z is known and is independent of the final fermion type. Thus, all visible Z^0 decays can be used for the precision test of the standard model. In Figure 1 the dependence on the Z mass of the left-right and forward-backward asymmetry is displayed. It is clear that the left-right asymmetry is much more sensitive to variations in M_Z than is the forward-backward asymmetry.

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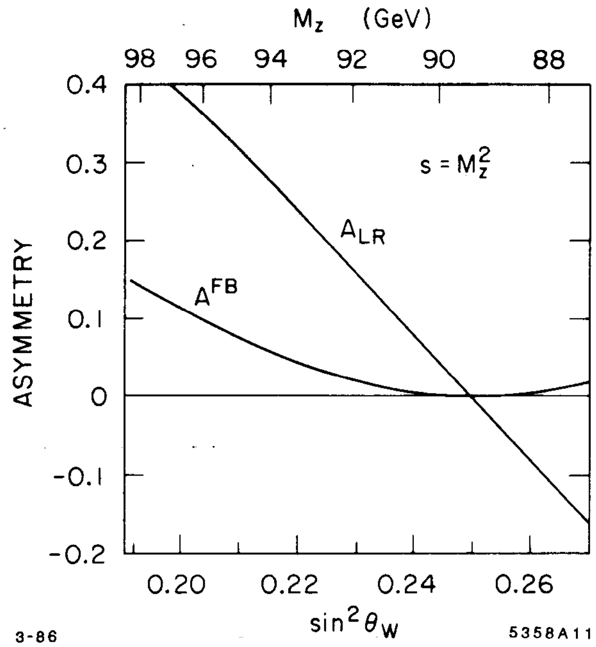

Figure 1. The left-right and forward-backward asymmetries evaluated at the peak of the Z, as functions of M_Z.

The accuracy of the measurement of A_{LR} depends on the uncertainty in the polarization measurement and statistics. The precision anticipated at the SLC is displayed in Figure 2 as a function of the number, N, of observed Z decays. The three curves correspond to different levels of precision when measuring the electron polarization. The scales on the right show the resulting precision of the A_{LR} measurement to those of $\sin^2\theta_W$ and M_Z. The left-right asymmetry will replace the ratio of neutral-to-charged currents for neutrino scattering as the best test of the standard model when the number of Z's is between one and ten thousand. Figure 2 also shows that A_{LR} has a luminosity advantage of almost one hundred in testing the standard model over the measurement of the forward-backward asymmetry of muon pairs. In addition the ultimate uncertainty of the A_{LR} measurement is about a factor 5 more precise than that of A_{FB}.

More details of the test of the standard model and other physics with polarized electron beams can be found in the papers of M. Swartz[1] and W. B. Atwood[2] submitted to this conference. In the paper by Atwood, the feasibility of using polarization to provide a handle for observation of $B^0 - \bar{B}^0$ mixing is presented.

OVERVIEW

The SLC has the capability of accelerating polarized electrons and transporting these through the damping ring to the interaction region with small depolarization of the beam. A collaboration of physicists from Indiana, LBL, SLAC and Wisconsin is preparing the systems for the polarization capability at the SLC.[3]

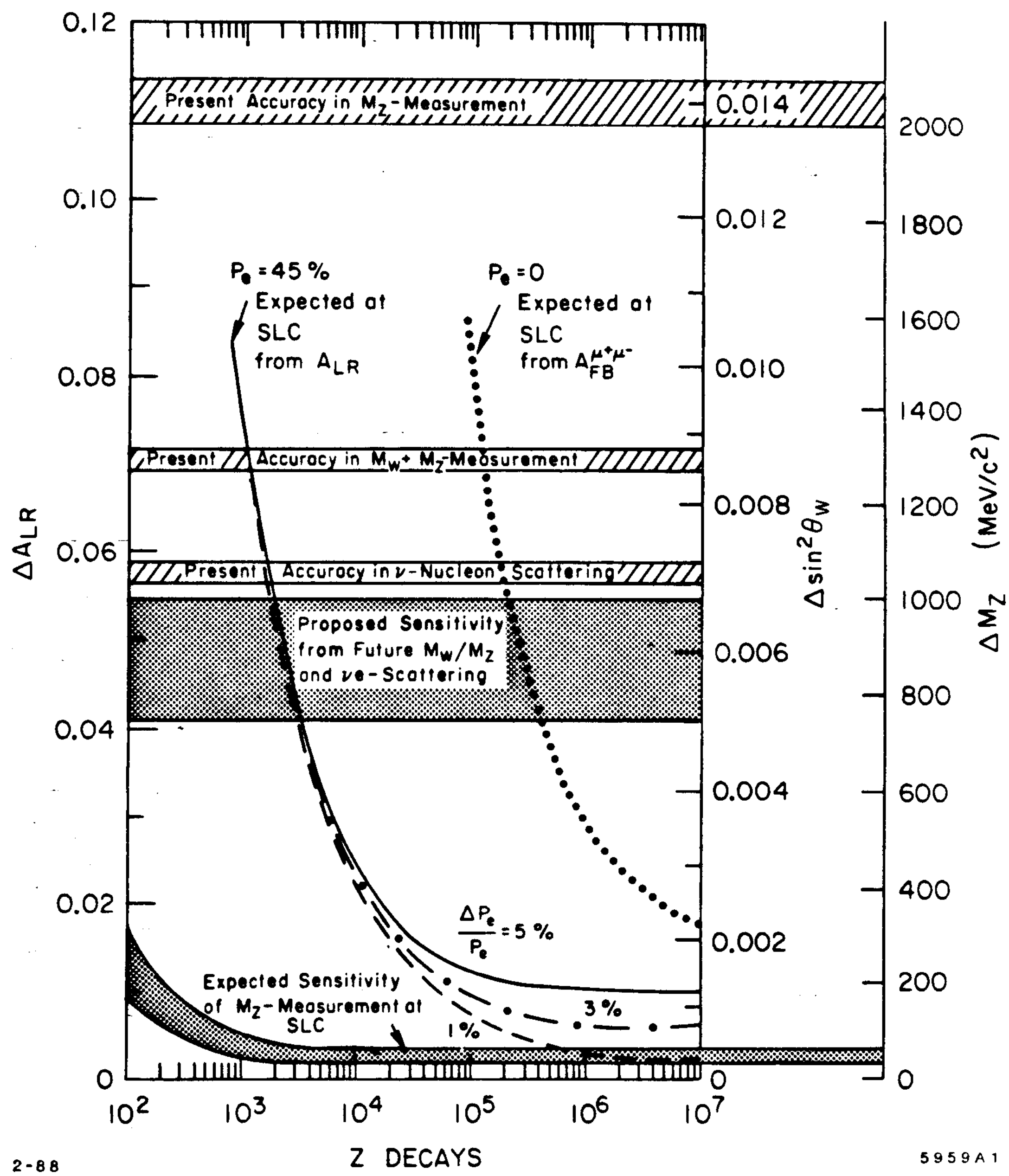

Figure 2. The expected uncertainty of a measurement of the left-right asymmetry A_{LR} as a function of the number of Z^0 events accumulated. The beam polarization is taken to be 45%. The Z^0 mass is assumed to be 92.5 GeV. The corresponding uncertainty on $\sin^2\theta_W$ and on M_Z is shown on the right-hand scales. The three branches of the A_{LR} curve refer to the precision of the polarization monitoring. The expected uncertainty on $\sin^2\theta_W$ from a measurement of the leptonic forward-backward asymmetry is also shown. The shaded regions indicate present accuracy and proposed sensitivity from M_W/M_Z measurements and ν-scattering. The shaded region at the bottom shows that the direct measurement of M_Z at SLC and LEP will be of sufficient accuracy to precisely calculate A_{LR} within the standard model.

The layout of the polarized SLC is shown in Figure 3. The electrons are produced longitudinally polarized by irradiating a GaAs crystal with circularly polarized light. The source will be capable of producing beams of the required intensity and pulse structure for SLC so no degradation of luminosity is expected.

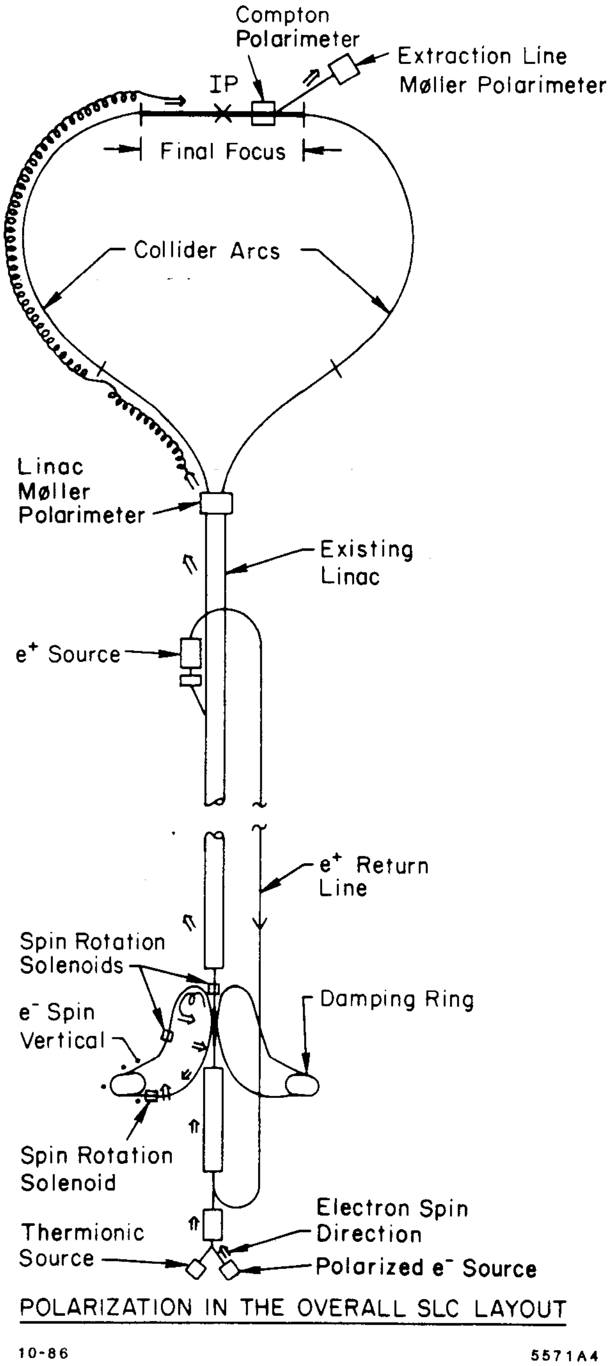

Figure 3. A layout of the SLAC Linear Collider emphasizing polarization. The orientation of an electron spin vector is shown as the electron is transported from the polarized electron source to the interaction point.

Polarization of about 45% is expected with this source. To preserve the polarization while the electrons are in the damping ring, the spin direction must be transverse to the plane of the damping ring. In addition, the spin direction must be reestablished after leaving the damping ring so that it points in the desired direction for acceleration to the end of the linac and transportation around the electron arc to the interaction point where longitudinal polarization is required (see Figure 4). A vertical spin component is required at some energies because of the terrain following of the arcs. Three spin-rotating solenoids of 6.34 T-m each are needed to rotate the spin. These superconducting solenoids are located at positions in the transfer lines to and from the damping ring where the spin direction has precessed 90° by the guide field. Compton and Møller polarimeters will be used to monitor and measure the polarization near the interaction point. In the following, some details of the systems are given. More details can be found in References 3 and 4.

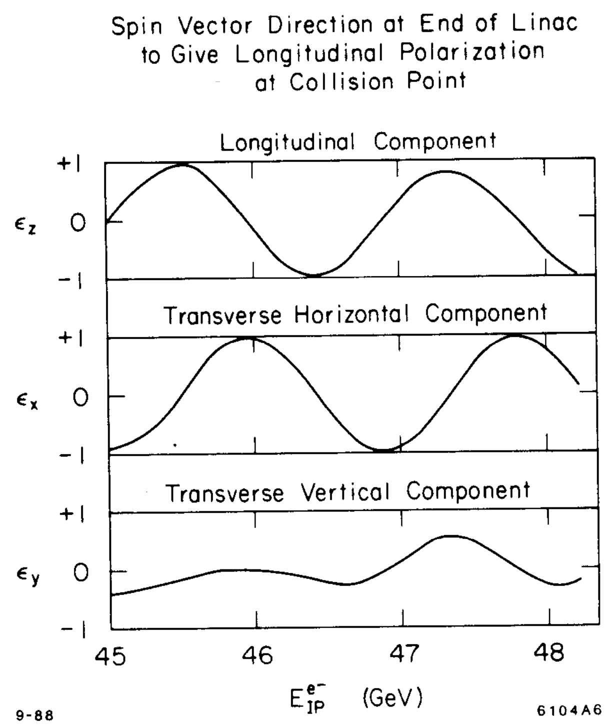

Figure 4. The spin vector direction at the end of the Linac to give longitudinal polarization at the collision point.

POLARIZED ELECTRON SOURCE

There are three important features of a gallium arsenide cathode:

i) The band structure permits a given spin state to be preferentially pumped into the conduction band. As seen in Figure 5 the $P_{1/2}$ state is lower by about 0.34 eV from the $P_{3/2}$ state. By illuminating the GaAs with light of energy slightly greater than 1.52 eV only transitions from the $P_{3/2}$ state to the conduction band are made. The different rates for the $m_j = 3/2$ and 1/2 levels are such that 50% electron polarization is produced by 100% polarized photons.

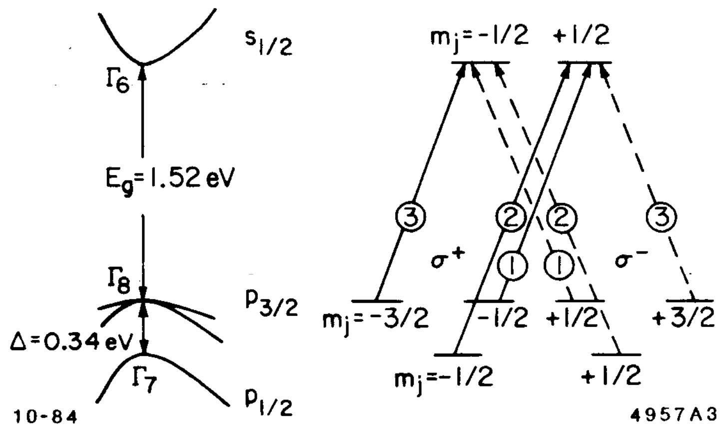

Figure 5. The band structure of GaAs near the bandgap minimum. The energy levels of the states are shown on the right. Allowed transitions for the absorption of right (left) circularly polarized photons are shown as solid (dashed) arrows. The circled numbers indicate the relative transistion rates.

ii) The polarization sense is reversible from pulse to pulse by selecting between left and right circularly polarized light.

iii) High quantum efficiency as large as 5% can be achieved by treating the GaAs surface to develop a negative electron affinity.

In practice, spin relaxation in the semiconductor reduces the polarization below the 50% limit. However, by using a very thin GaAs cathode, polarization approaching the 50% limit can be obtained (see Figure 6).[5] Above a wavelength of $\approx$ 740 nm the polarization is flat at about 48%. At the longer wavelengths the quantum efficiency continues to decrease.

Figure 7 shows the layout of the polarized source and the thermionic unpolarized source at the injector of the SLC along with the laser and light path. Fast exchange between sources has been planned. The polarized source was installed on the accelerator more than two years ago after meeting all specifications in the laboratory. Since that time the commissioning of the SLC has not allowed time for the laser to be installed. However, the GaAs photocathode has been activated and its quantum efficiency measured to be about 1%. A cathode lifetime of approximately 1000 hours with the source isolated decreases to only 100 hours when exposed to the accelerator environment. Improvement to the accelerator vacuum will be required.

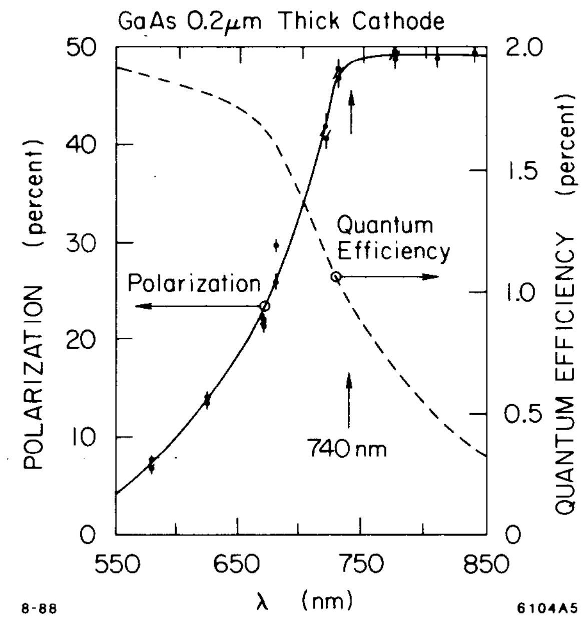

Figure 6. Polarization and quantum efficiency as a function of the wavelength of the incident circularly polarized light on a thin GaAs cathode of 0.2 micron thickness.

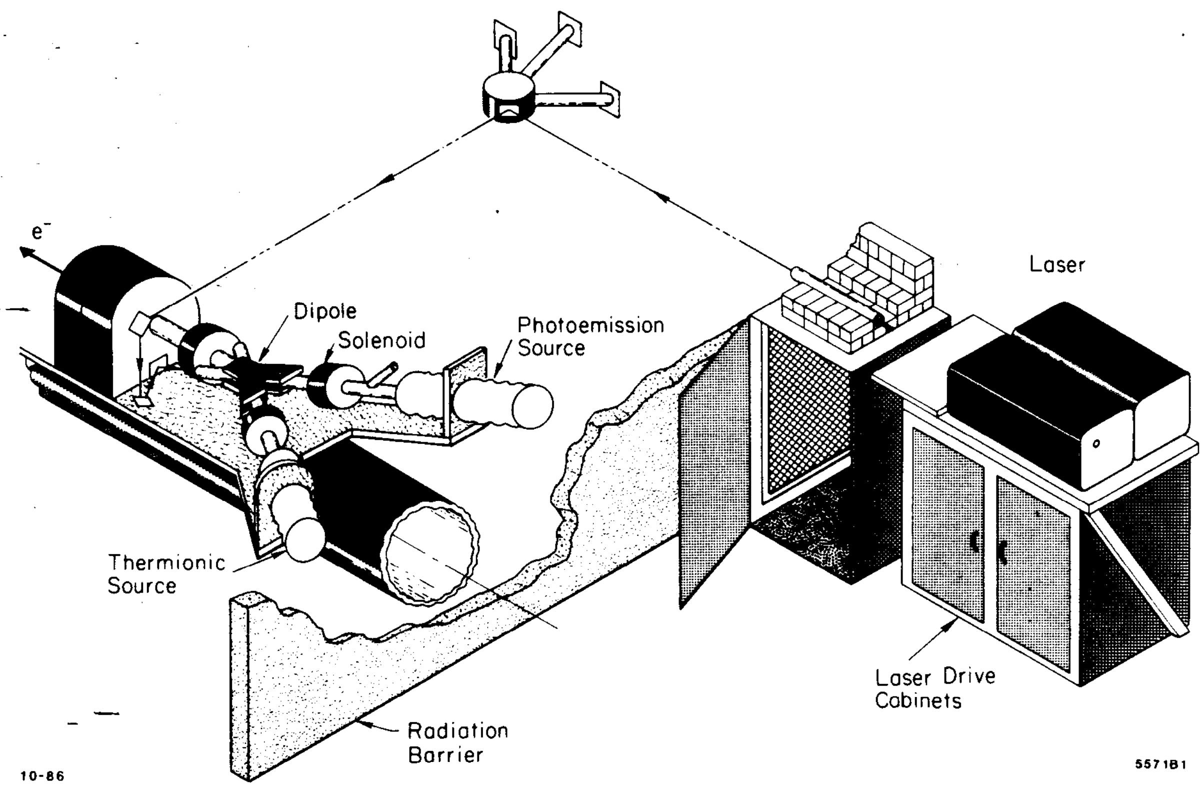

Figure 7. Layout of the polarized electron source and the thermionic unpolarized gun at the SLC along with the laser and light path.

The laser which drives the polarized source is being commissioned in the laboratory. It is a flashlamp-pumped dye laser which gives a peak power of about 70 kilowatts (2.7 kW are required to deliver the required 10^{11} electrons from a 0.5% quantum efficient cathode). Two $\sim$ 2.5 ns bunches separated by $\sim$ 60 ns are needed for each of the 120 hertz machine pulses. Detailed studies of two dyes have been made and some results are shown in Figures 8 and 9. The laser output

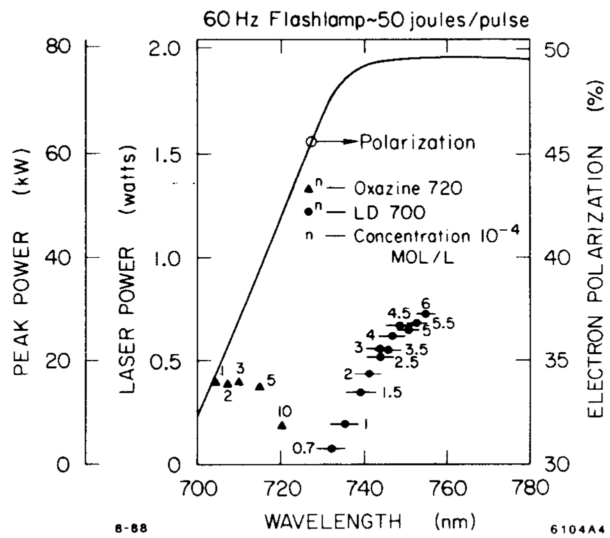

Figure 8. Power of the SLC laser is shown as a function of wavelength for two different dyes. The numbers next to the data points refer to dye concentration. The curve taken from Figure 6 shows the electron polarization as a function of wavelength.

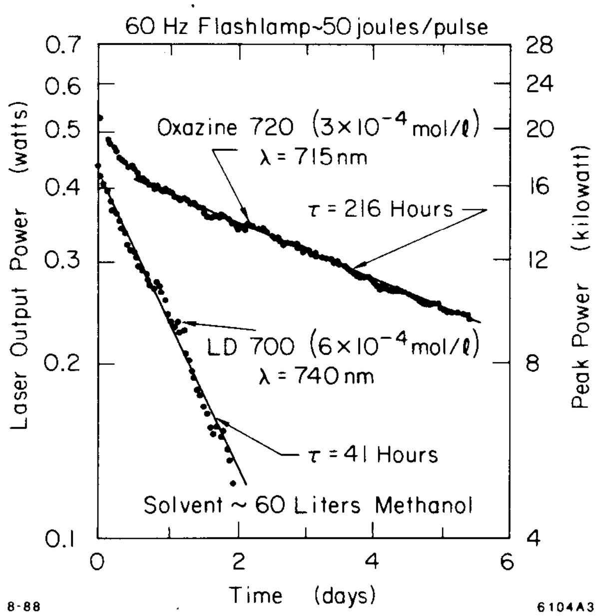

Figure 9. Laser output power as a function of time for two different dyes.

power is excellent for both dyes but only LD700 can reach above 740 nm where the highest polarization is achieved. However, the LD700 dye degrades more rapidly than Oxazine 720 as seen in Figure 9. The status of the commissioning effort in achieving the required specifications is summarized in Table I. During the last two years the laser and its support equipment have undergone extensive modifications to make them more reliable and safer, and this effort will continue.

Table I. Status of LASER in meeting the specification for the polarized source.

Item	Specification	Status
Peak Power	2.7 kW	ok
Wavelength	740 nm	ok
Repetition Rate	120 Hz	ok
Pulse Width	2.5 ns	Best 5 ns
Pulse to Pulse Intensity Jitter	$\frac{\Delta N_e}{N_e} = \pm 0.5\%$	$\frac{\Delta N_\gamma}{N_\gamma} = \pm 1.5\%$
Time Jitter	30 ps	unknown
Time between maintenance	$\sim$ 1 week	marginal
Reliability	5000 hours/year	Continuing effort

A modulator consisting of a Pockel cell between crossed polarizers is used to chop out the two short pulses from the 0.6 μsec laser pulse. The scheme for doing this is shown schematically in Figure 10. The modulator is operational, but the existing high voltage driver to the Pockel cell requires modification to reach the desired pulse width.

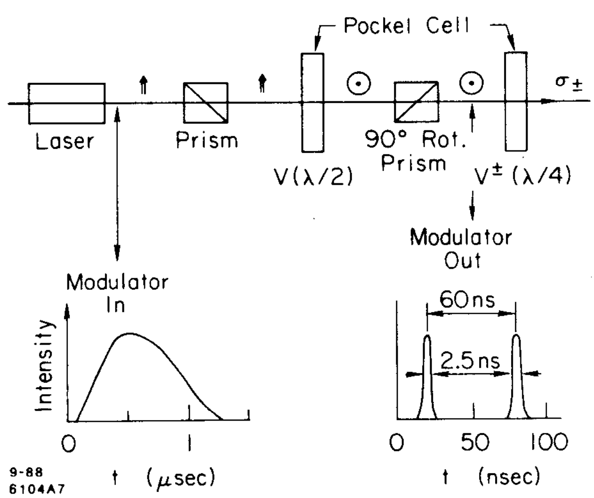

Figure 10. The short pulse modulator and circularly polarizer for the SLC polarized source.

SPIN ROTATION AT THE SLC

Electrons, before being delivered to the SLC interaction point, are stored between beam pulses in the damping ring, where their energy is 1.21 GeV. The only spin direction that can be preserved in such a ring is parallel to the magnetic field, that is, transverse to the plane of the damping ring.

The electrons are longitudinally polarized at the source and during acceleration through the first sector of the Linac before being transferred to the damping ring. At 1.21 GeV, the electron spin component in the plane normal to an applied magnetic field will precess 90° in that plane for every 32.8° of rotation of the momentum vector. An axial solenoidal field integral of 6.34 T-m is then needed to rotate the spin parallel to the field of the damping ring; i.e., by 90°. In the linac-to-ring (LTR) transfer line this solenoid will be located after a bend of $5 \times 32.8°$ as seen in Figure 11. To reestablish longitudinal polarization after damping another solenoid will be installed very close to the exit of the damping ring and the in-plane precession will be accomplished by a subsequent bend of $3 \times 32.8°$.

With a third solenoid, located in the Linac line just after the beam is injected back into the Linac, arbitrary spin directions for acceleration can be achieved. Figure 4 shows the required spin direction at the end of the Linac as a function of energy to achieve longitudinal polarization at the interaction point. If there is no significant depolarization of transverse polarization components in the linac, the combination of the RTL and Linac solenoids permits one to have longitudinal polarization at any energy at the interaction point.

Adding solenoids to the LTR and RTL transfer lines and to the Linac affects the optics of these systems. This is due to the optical transfer matrix for a solenoidal field being represented by a focusing element and a rotation of the beam coordinate system about the beam axis. Some modifications are needed in the optics to compensate for the effects of the insertion of a solenoid. These changes are shown symbolically in Figure 12.

The three superconducting solenoids were delivered to SLAC in late Spring of 1988 and have passed the following acceptance tests:

1. Integral of the axial magnetic field reaches 7.2 T-m.
2. Magnetic field is purely solenoidal to one part in a thousand.
3. No fringe field outside of ferromagnetic shield.
4. Magnetic axis is reproducible to 100 microns after warmup and cooldown.
5. Heat leak is less than 1 watt and the helium reservoir is sufficient to run 24 hours between liquid helium fills.

The cryogenic and magnet protection systems are complete and have met all the requirements. The magnets are being commissioned in the laboratory in a setup simulating the damping ring. As a result the operation of the solenoids and improvements to the support equipment will be well understood when they are installed.

The engineering, design and fabrication of the items required for the electron beam optics changes are in progress. The new quadrupoles have been fabricated and the power supplies for independent quadrupole control are on order. Detailed plans for installation have been prepared. The installation of the spin rotation systems is presently scheduled for the summer of 1989 but the final decision depends on the progress of the SLC commissioning.

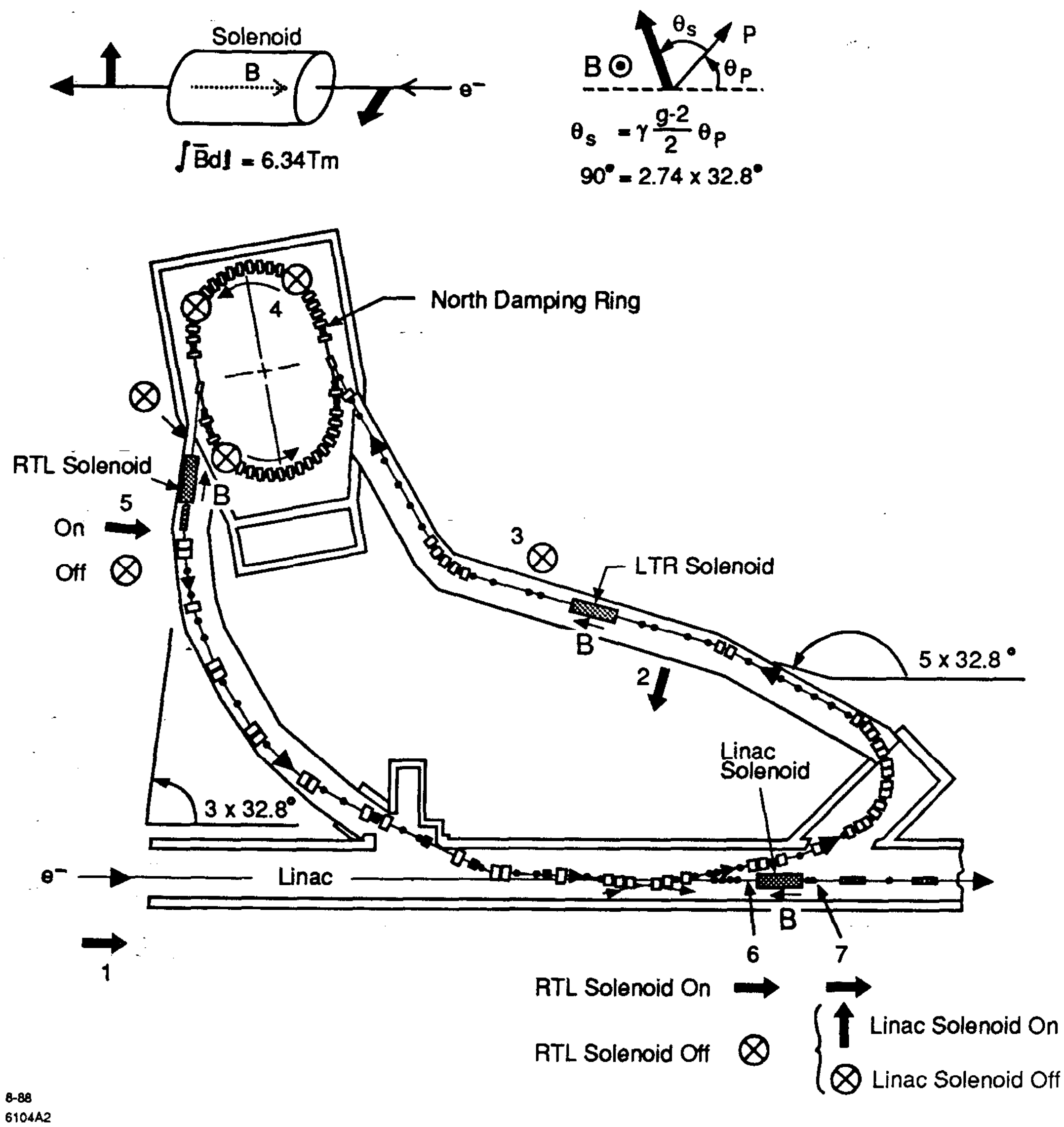

Figure 11. The spin rotation system for the north damping ring. The orientation of the electron spin vector is shown by the full arrow.

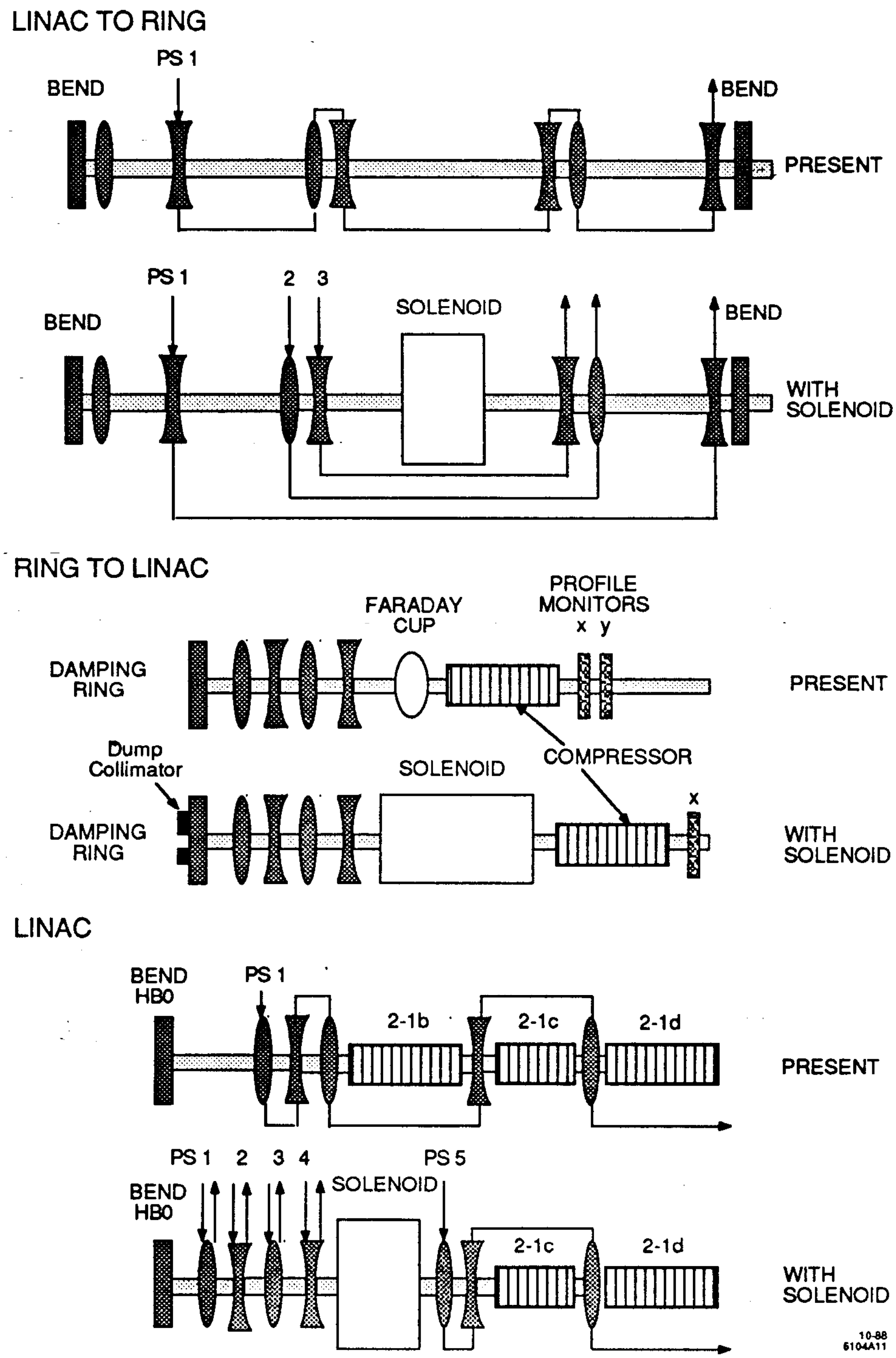

Figure 12. Changes to the electron beam optics to compensate for the effects of the insertion of the solenoids.

POLARIMETRY

Two types of polarimeters based on Compton and Møller scattering will provide reliable and accurate polarization measurements near the interaction point (see Figure 13). A third Møller polarimeter at the end of the Linac will serve as a useful diagnostic tool in tuning the polarization and in defining the initial spin vector. Both Møller polarimeters are capable of measuring all three components of the polarization vector.

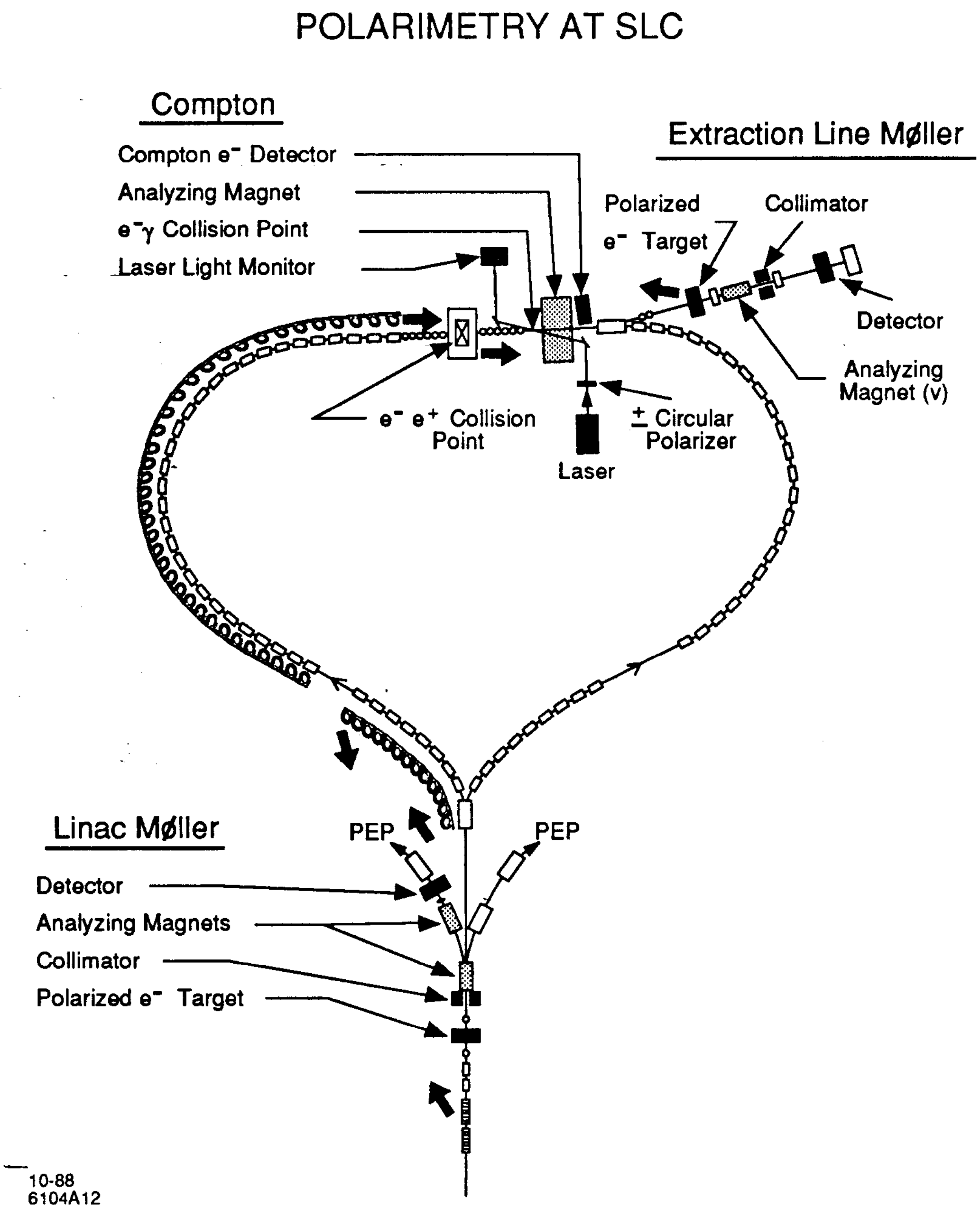

Figure 13. Location of the polarimeters at the SLC. The elements of the polarimeters based on Møller and Compton scattering are indicated.

The Møller polarimeters are well suited for use at the end of the Linac and in the extraction line before the beam dump. The advantages are that the technique has been demonstrated in previous experiments with polarized beams at SLAC[6] and it gives three-axis polarimetry. Figure 14 shows the center of mass scattering angle dependence of $d\sigma/d\Omega^*$ and $\cos\theta^*$. While the counting rate (50 to 100 Møller scatters detected per electron pulse) and the asymmetry (longitudinal asymmetry is 0.78 at 90° in the center of mass) are large the target polarization is only about 8%. This means that the measured asymmetry is only about 2% when the beam

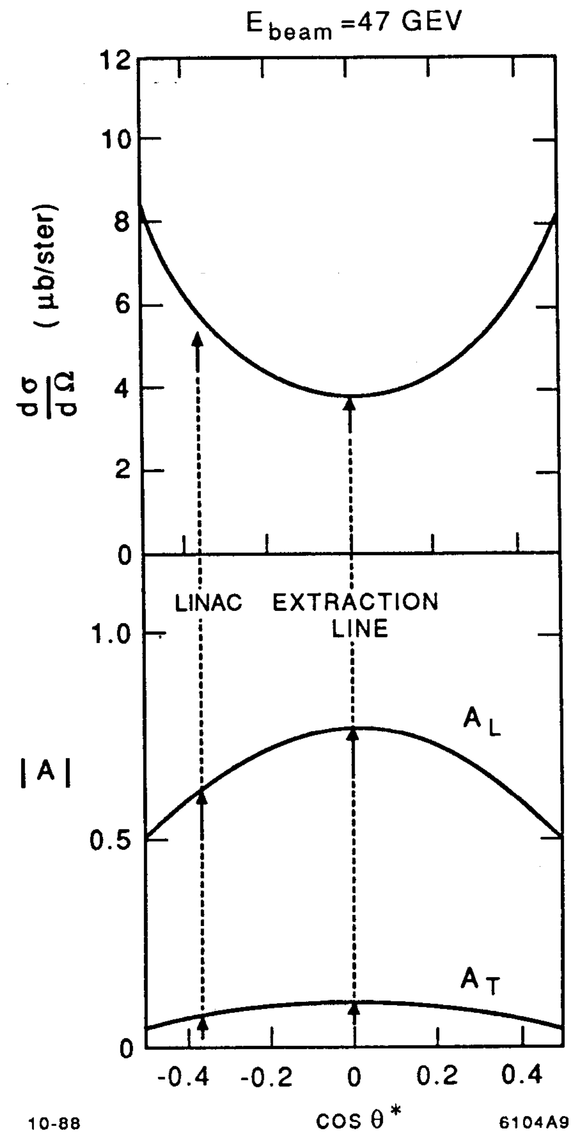

Figure 14. Differential cross section and asymmetry of Møller scattering as a function of the scattering angle cosθ, in the center of mass. The extraction line polarimeter takes Møller scatters at 90° (cosθ* = 0) while the Linac Møller works at 110° (cosθ* = – 0.34).*

has polarization of 0.4. Longitudinal polarization of the beam can be measured to an accuracy of $\Delta P/P = \pm 5\%$ in one or two minutes while transverse polarization will require about 1 hour to reach the same accuracy due to a lower asymmetry of 1/7 than that for longitudinal spins.

Data from the SLAC e^-D experiment[6] is shown in Figure 15 and demonstrates one of the limiting features of this technique. The subtraction of the background from electron-iron scattering leads to an uncertainty of $\Delta P \approx \pm 2\%$. The other major contribution to the systematic error is the uncertainty in the measurement of the target polarization ($\Delta P \approx \pm 2\%$). Other contributions to the systematic error due to radiative corrections, detector response and target spin disruption as the beam passes through are estimated to be small.

The targets, collimators and detectors for the Møller polarimeters are prepared and the components of the Linac polarimeter are installed. Background studies are in progress. Installation of the extraction line Møller components is awaiting authorization.

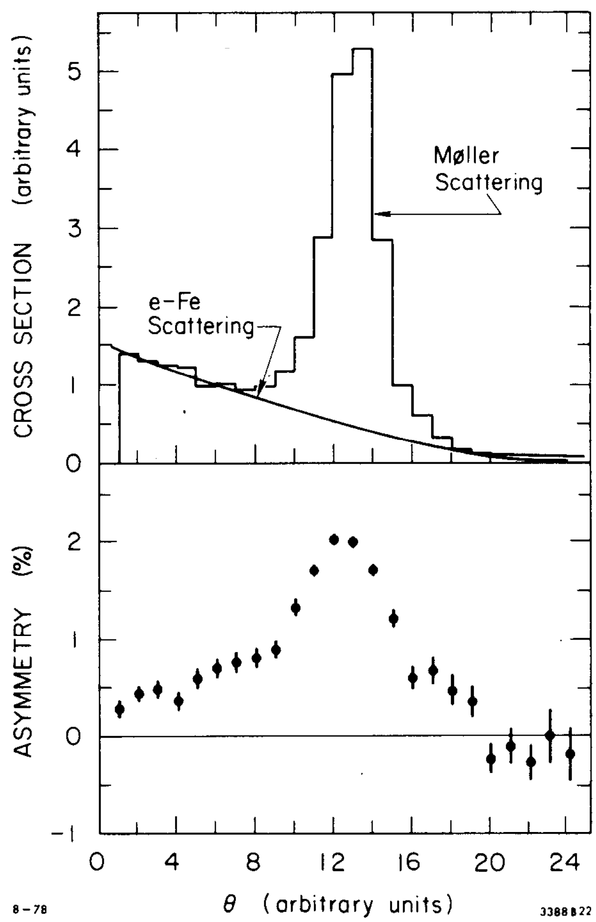

Figure 15. The cross section and asymmetry measured with the Møller polarimeter used in the e^-D experiment. The Møller polarimeters for the SLC are similar in design to that used to collect this data.

A polarimeter making use of the Compton effect can be used to measure the absolute electron polarization to about 1% accuracy, and to monitor rapidly relative changes in polarization during operation. Such a polarimeter is being prepared to monitor the electron polarization near the IP (see Figure 16). A circularly polarized laser beam intercepts the electron beam 107 feet downstream of the interaction point. Recoiling electrons at the maximum Compton angle emerge directly forward in the laboratory with momentum less than half that of the beam, from which they are separated in the field of the soft and hard

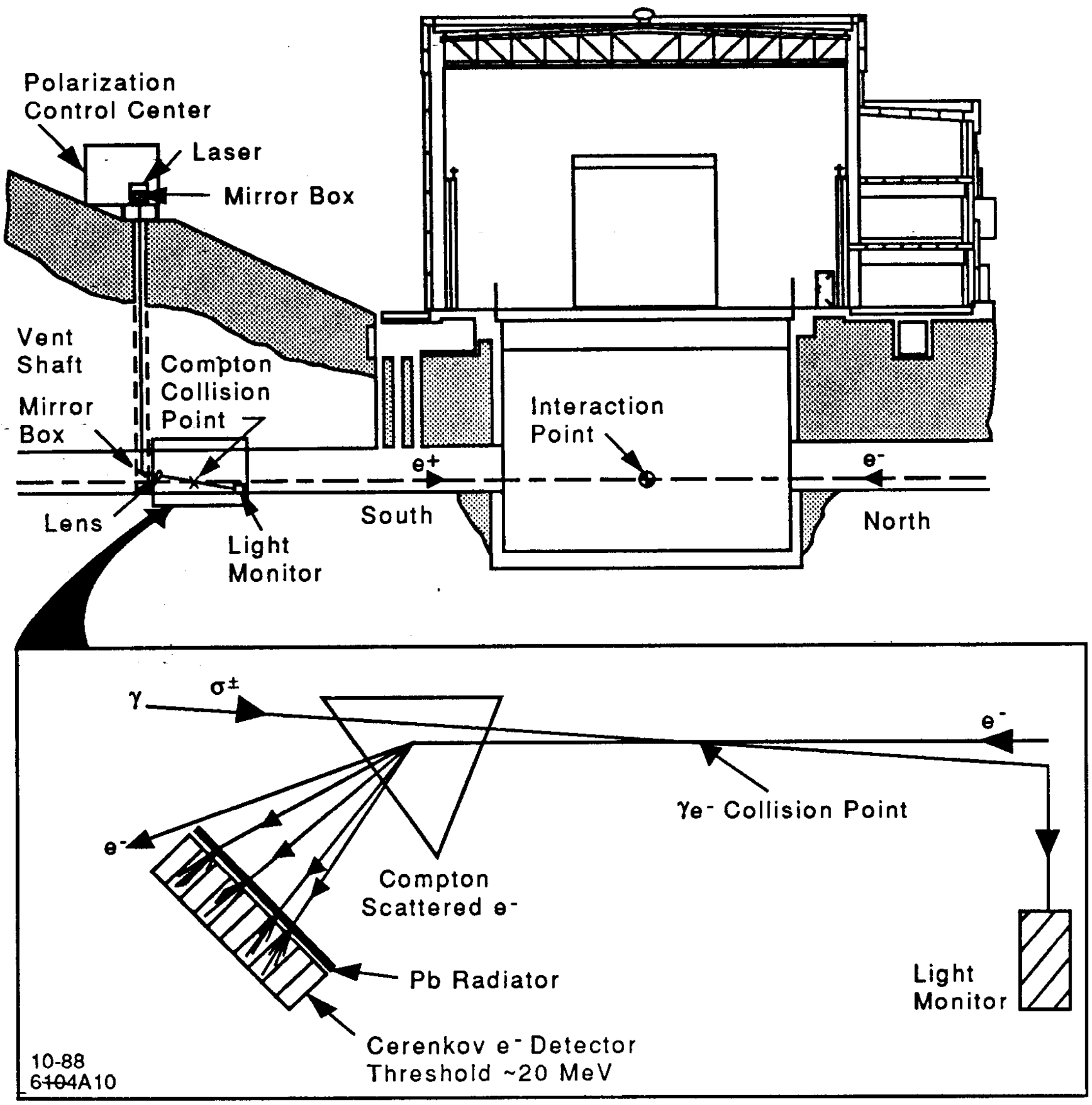

Figure 16. Location of the SLC Compton polarimeter components is shown. The light from the laser on the surface is directed into collision with the electron beam after it has passed through the interaction point.

bend magnets as they head toward the electron dump. The asymmetry of the reaction rate, when either photon or electron polarization is reversed, can be 75% or higher for backward Compton scattering. The counting rates are high. The known backgrounds are expected to be tolerable and can be explicitly subtracted by using spills when the laser is not pulsed. A sufficient number of counts to achieve 1% statistical accuracy can be accumulated in a few tens of seconds. The SLC Compton Polarimeter can only measure the longitudinal component of the beam spin vector.

Preparation of the systems of the Compton polarimeter are in progress. The polarization control room which houses the laser and detector electronics has been available for the last year. The YAG-laser from the SLAC back-scattered photon beam facility will be used initially and it is planned to move it to the laser room this Fall. The elements of the light path have been prepared and some are installed. A prototype Cerenkov detector was installed a year ago and background studies have been made. These studies have shown the need for changes to the detector design and shielding of the phototube. Signals from the electron beam on the wire scanner used for SLC tuning and from the radiative Bhabha scattering simulate Compton electrons for these studies.

DEPOLARIZATION EFFECTS

Depolarization of the beam can occur during the acceleration and transport of the beam to the interaction region. Most of the depolarization effects are small such as those during acceleration and in the damping ring when depolarizing resonances are avoided. However, there are two effects which cause moderate depolarization. The first of these is due to the damping ring running at 1.153 GeV instead of the design value of 1.21 GeV. As a result the spin precession in the linac to ring is smaller and the spin vector is not quite perpendicular to the beam direction as the beam enters the LTR solenoid. Until the ring can operate at 1.21 GeV a 0.069·P depolarization will occur. The other significant depolarization effect is caused by the finite energy spread ($\Delta E/E = \pm 0.2\%$) of the beam; the γ(g-2) factor in the spin precession gives a spread in the spin vector at the end of the arc resulting in a 0.021·P depolarization effect.

There can also be depolarization from the beam-beam collisions and the final focus system element, but with SLC parameters, these effects are negligible.

DETECTORS AT THE SLC

Two detectors will take data at SLC. The Mark II will take data initially.[7] A new SLD detector[8] is being built to replace the Mark II. Both detectors have charged particle tracking and photon detection over nearly 4π solid angle. The SLD detector goes beyond the Mark II in having hadron calorimetry and full particle identification.

The polarization sign and the average longitudinal polarization will be recorded with each Z^0 and luminosity event. The left-right asymmetry can then be determined from the analysis of these data. The demands on the detectors from the point of view of the left-right asymmetry measurement is minimal, namely, the acceptance must be forward-backward symmetric.

SUMMARY

It is natural to incorporate polarization on the SLC without significant impact on machine performance. The hardware for the source, spin rotation and polarimetry is in an advanced state of preparation. The installation schedule is determined by the progress of commissioning the SLC.

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