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REVIEW OF SLC PERFORMANCE*

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Abstract

The SLAC Linear Collider (SLC) has begun a new era of operation with the SLD detector. During 1991 there was a first engineering run for the SLD in parallel with machine improvements to increase luminosity and reliability. For the 1992 run, a polarized electron source was added and more than 10,000 Zs with an average of 23% polarization have been logged by the SLD. This paper will discuss the performance of the SLC in 1991 and 1992 and the technical advances that have produced higher luminosity. Emphasis will be placed on issues relevant to future linear colliders such as producing and maintaining high-current, low-emittance beams and focusing the beams to the micron scale for collisions.

Introduction

The SLAC Linear Collider (SLC) is a pioneering machine which has demonstrated the viability of linear collider technology for the next generation of high-energy electron-positron accelerators. Construction of the SLC was completed in 1987 and, after two years of commissioning, the first physics run with the Mark II detector began in 1989. In late 1990, the Mark II experiment was complete and the new state-of-the-art SLD detector was installed. During 1991 there was a first engineering run for the SLD combined with an intensive program of machine development resulting in a factor of 4 increase in the peak luminosity and greatly improved reliability. For the 1992 run, a polarized electron source was installed and successfully commissioned. Average luminosity has increased by another factor of 4 and further improvements are expected from higher beam intensities and better optimization of beam size at the interaction point.

Polarization at the SLC

The SLC polarized source,[1] produces longitudinally polarized electrons by illuminating a GaAs photocathode with circularly polarized photons from a dye laser. Three superconducting solenoids are required to deliver a longitudinally polarized beam to the interaction point (IP). The first solenoid in the Linac to Ring (LTR) transfer line rotates the electron spin direction into the vertical before injection into the Damping Ring. Two solenoids in the Ring to Linac (RTL) transfer line and at the entrance to the Linac are used to orient the spin direction on injection into the Linac so that after the spin precesses through the Arcs, the electrons are longitudinally polarized at the IP. A Moller polarimeter measures the beam polarization at the end of the Linac. A Compton polarimeter measures the longitudinal component of the polarization near the IP.

The diode gun was built, tested and installed on the SLC in early April 1992. This gun has a bulk GaAs cathode with an expected polarization of 27–29% at the gun. The cathode

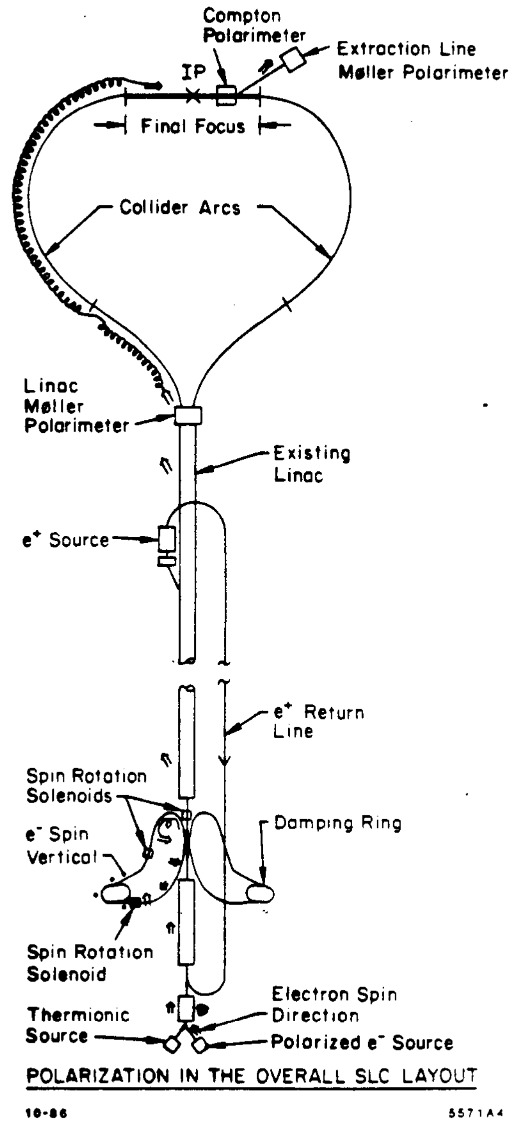

Fig. 1. Schematic of the SLC showing components of the polarized source, beam transport, and diagnostics. Spin orientation is indicated by the arrows.

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the SLC with polarized beam began April 18. The cathode was activated and longitudinally polarized beam transported straight down the Linac to the Moller polarimeter bypassing the Damping Ring. A polarization of 28±1% was measured consistent with no loss of polarization in the Linac. Beam was then brought through the Damping Ring complex and spin rotators where the polarization transmission factor is predicted to be 92% due to the slightly lower than optimal operating energy of the rings and LTR. Polarization at the end of the Linac was about 26% showing no anomalous depolarization.

By April 21, the polarized beam was transported through the North Arc to the Compton polarimeter. Calculations had predicted that at 45.6 Gev the spin orientation would be almost fully longitudinal at the IP with the RTL spin rotator set to rotate 90 degrees and the Linac spin rotator at zero. However with these settings, initial measurements with the Compton polarimeter gave essentially zero polarization. The experimenters then mapped out the polarization as a function of the beam energy and found that the spin precession through the Arcs was nearly 90 degrees more than predicted. Further studies showed a strong dependence of the spin orientation on the beam orbit through the Arc, especially in the vertical plane. Different settings of the RTL and Linac spin rotators were used to orient the spin vector in the Linac in three orthogonal directions: vertical, horizontal and longitudinal. The longitudinal component of the polarization at the IP was measured for each orientation of the spin vector to reconstruct the empirical spin precession through the Arc and determine the optimal settings for the spin rotators. A peak polarization of 24–25% was measured indicating a few percent relative depolarization through the Arc and Final Focus systems.

Polarized Gun Performance

After the successful commissioning, the SLC began a physics run with the polarized source. The first weeks were spent tuning up the laser and injector performance for routine operation and determining running parameters to optimize both efficiency and luminosity. The gun has now been operating for four months without any high voltage problem and minimal downtime (93% efficiency). The primary problem for machine operation is higher intensity jitter (and therefore energy jitter) from the polarized source. There is also a slight increase in the beam emittance due to the difficulty of matching the optics through the spin rotators.

Routine maintenance includes recesiation of the photocathode, renewal of dye and flashlamps for the laser, and periodic heat treatment and reactivation. The initial quantum efficiency (QE) after cesiation is 8–10% which then drops about 1% per day. The gun is typically recesiated at a QE of about 3% when intensity jitter begins to interfere with machine stability. Recesiation takes 2 hours every 5–7 days. The laser dye and flashlamp change takes 4 hours every two weeks. Reactivation and heat treatment requires an 8–10 hour intervention once a month. Wherever possible, other routine maintenance activities are scheduled to overlap with the gun work so the presence of the gun has had a negligible impact on overall machine downtime.

A major concern to date has been the lack of a backup gun but the first of two rebuilt guns is now successfully through high voltage processing and both guns are expected to be ready in August.

Prospects for Higher Polarization

The present cathode is Bulk GaAs with a polarization at the cathode of 27–29% at 0° C with operational quantum efficiency. After transport through the Damping Ring and Arcs, the polarization at the IP is only 24–25% peak, or 23 ±1% in typical operation. The depolarization effects are multiplicative so one can only expect 85–90% of the polarization at the cathode to be delivered for physics. Several candidates for higher polarization cathodes are under study (Table 1).

Table 1. Cathode options for higher polarization.

Cathode	Polarization at Cathode
Bulk GaAs at 150° K (715 nm)	42 %
Thin AlGaAs (715 nm)	42 %
Thin GaAs (760 nm)	45 %
Strained lattice [2] (830 nm)	85 %

All values are for expected polarization at the cathode at 0° C except where noted. For the longer wavelength options, a new laser is required. A Ti:Sapphire [3] laser pumped by a doubled YAG laser has been constructed and will be ready for installation in September. In addition to providing a tuneable wavelength, this laser has a factor of 100 more power and a better mode structure which should allow stable operation at lower quantum efficiency.

Present plans are to install an AlGaAs cathode on the next gun with the possibility of a test run on the accelerator before the Fall shutdown.

1991 Performance

The 1991 SLC run began with an extended period of intensive machine development while the SLD detector installation was completed. As part of the SLD installation, new superconducting quadrupoles were installed for the final focusing telescope near the IP. After recommissioning the Arcs and Final Focus, there was a brief 6 week engineering run with the new detector. The machine repetition rate was limited to 60 Hz during the entire run due to budget constraints. By the end of the run, the luminosity per pulse was a factor of 4 higher than in 1990 and operating efficiency was dramatically improved with a machine uptime of nearly 60%. New records were achieved for electron and positron intensity, positron yield, low emittance at the end of the

Linac, and small beam size at the IP. An estimated 1500 Zs were delivered by the SLC with about 25% logged by SLD.

1992 Run Status

The 1992 run began in January, with two months of recommissioning and machine development studies. The machine repetition rate was raised to 120 Hz in early February. In March, SLD logged 1000 Zs with unpolarized beam. The polarized electron gun was installed and commissioned in April. The SLD physics run began in May and will continue through mid-August. The last month of the run will focus on machine development to provide higher luminosity and higher polarization for 1993. During the SLD run, there has been a steady increase in the luminosity from primarily adiabatic improvements in intensity, beam size, and tuning efficiency. The average luminosity is a factor of 4 higher than in 1991, while the rate of data logged by SLD has improved even more dramatically. More luminosity is logged on a typical day than in the entire 1991 run. The biggest gains have come from 120 Hz operation (a factor of 2 in luminosity), machine uptime (60–70%), and higher efficiency for SLD logging due to a better integration of the machine and the detector and better control of backgrounds. Benefits from improvements in beam intensity, emittance control and tuning techniques have slowly produced another factor of 2 in luminosity, but dedicated machine development studies will be required for further progress.

Luminosity Issues

<u>Positron Yield</u>

A major limitation to performance in 1990 was low positron intensity. The figure of merit for the positron production system is the yield of positrons in the Linac (exiting the South Damping Ring) per electron incident on the target. In 1989 and 1990, the positron yield was typically about 0.6. Additional beam position monitors and stronger steering dipoles were added to provide better control of orbits in the critical Linac to Ring transfer line. In early 1991, a careful study of the apertures and optical matching throughout the positron system was carried out. By reversing the polarity of the positron damping ring magnets, a narrow electron beam could be used to map the ring and transfer line with much higher precision than would be possible with a large emittance positron beam. Limiting apertures were identified and corrected and a peak yield of 1.25 was achieved.[4] In typical operation, a yield greater than 1.0 can be maintained with little effort. This results in a factor of 2 higher positron intensity for collisions.

<u>Beam Intensity</u>

The polarized source has delivered over 4 10^{10} electrons per bunch and higher intensities should be achievable with the new laser. The present limit on beam intensity which can be delivered for collisions is set by the onset of a microwave bunch length instability observed in the Damping Rings at an intensity of 3 10^{10} particles per bunch. During the damping cycle, the bunch length shrinks until a critical current density is reached and turbulent bunch lengthening occurs. The longer bunch is then stable and damps until the threshold is reached again, producing a "sawtooth" profile on a trace of bunch length vs. time. The number and frequency of the blowup cycles depends strongly on the bunch intensity causing small fluctuations in intensity to translate into large fluctuations in bunch length and phase at extraction. By ramping the RF voltage down after the bunch is captured, the bunch length may be kept above threshold. The RF voltage is then ramped up to shorten the bunch before extraction. This technique has allowed stable operation with bunch intensities up to 3.5 10^{10}. Further studies are needed to explore the operational limits.

<u>120 Hz Operation</u>

The SLAC Linac is powered from the local electrical grid with 3 phases of 60 Hz power, providing six timeslots for 360 Hz operation. At 120 Hz, alternate beam pulses are at different zero crossings of the 60 Hz AC power, causing what is referred to as timeslot separation. This can cause subtle differences in the behavior of klystrons, kickers, power supplies, etc., which result in different energy or trajectory characteristics for the two different timeslots. The first line of attack is to identify devices sensitive to timeslot and modify them to eliminate the sensitivity. Special controls have been implemented for critical energy and phase parameters to tune out the residual differences. In particular, the feedback which keeps the beams in collision at the IP can make different orbit corrections on alternate pulses using pulsed dipoles.

Another long-standing problem with 120 Hz operation at the SLC is the onset of a 2 bunch π-mode instability in the Damping Rings at high intensity. (At 120 Hz there are two bunches stored in each ring for each machine pulse.) This has been cured by the installation of a passive damping cavity in both rings.[5] Finally, there is a slight increase in the emittance of the electron beam due to it not being fully damped after 1/120 second. Overall, 120 Hz operation has produced nearly a full factor of 2 increase in luminosity.

<u>Beam Emittance</u>

Producing high-current, low-emittance beams and transporting them without increasing the emittance is one of the most difficult challenges of a Linear Collider.[6] The beams must be carefully matched through the transport lines from the damping rings into the Linac lattice. Because of the inherent energy spread of the particles in the beam, unmatched beams filament as they are accelerated down the Linac, causing an increase in the effective emittance. Four wire scanners [7] in the first few feet of the Linac measure the beam size at different betatron phases and provide a calculation of the beam emittance and matching. Trajectory data taken at different energies are used to measure residual dispersive and chromatic terms. With these techniques the beams were successfully matched to second order in 1991,[8,9]and with the addition of octupoles, to third order in 1992. Four wire scanners near the end of the Linac and others along the Linac provide further diagnostics for monitoring and measuring beam size.

Once the beams are matched into the Linac lattice, the beam trajectory must be centered to within 100 microns to prevent wakefield growth. Fits to orbit data from both electron and positron beams in the Linac allow a measurement of the offsets of quadrupoles and beam position monitors with respect to the beam line.[10] These devices have then been aligned to less than 100 microns. Alignment of the accelerator structures is also critical and because these structures and their supports can deform as a result of temperature gradients, the alignment must be done at the operating temperature of the machine.[11] The beam trajectories throughout the machine are maintained by an extensive network of feedback loops. In 1991, most of these feedbacks were upgraded to a new system which operates at 10–120 Hz.[12] Wakefield tails caused by residual misalignments have been canceled successfully by introducing a controlled trajectory oscillation to generate beam errors of the opposite phase.[13] Invariant emittances of less than three 10^{-5} meter-radians have been achieved for both beams with beam intensities of 3 10^{10} per bunch at the end of the Linac

Arc Optics

From the end of the Linac, the beams are transported through the SLC Arcs and brought to the Final Focus. The Arcs follow the elevation of the local terrain while curving towards the IP. This creates non-planar transport lines which have presented a particularly difficult problem during SLC commissioning. A new technique developed in 1990 allowed a reconstruction of the entire optical transport matrix through the Arcs from a fit to trajectories taken with induced oscillations in the horizontal and vertical planes.[14] From the measured matrix, optical errors in each achromat can be corrected using calibrated closed bumps to introduce compensating errors. With this technique, the Arcs have been restored to the design optics with less than 5% anomalous emittance growth.

Final Focus

In 1991, with the new superconducting final quadrupoles [17] and standard tuning to eliminate coupling, dispersion and chromatic aberrations, the beams were focussed to a size of about 2 microns. This provided a factor of 2 improvement in the specific luminosity. To reach the minimum beam size with nominal emittances, the angular divergence must be 300–350 microradians where the upper limit is usually restricted by excessive backgrounds in the detector. With the Mark II detector, the divergence was limited to less than 220 mrads, but the SLD has successfully run with up to 350 mrads allowing more latitude for beam optimization. At very small beam sizes, the minimum size achievable is limited by optical aberrations from misaligned magnetic elements, particularly the sextupoles. A new technique [16] uses the measured change in focusing, dispersion or coupling with sextupole strength to deduce the misalignments. This method has higher precision than typical alignment using beam orbits with a resolution of < 100 microns. Beam sizes of 1.9 by 1.2 microns for electrons and 1.7 by 1.4 microns for positrons were measured. For luminosity running, an average beam size of 2 microns is routinely achieved.

Efficiency

Machine operating efficiency was greatly improved in 1991, with nearly 60% uptime for the entire run. This efficiency was the result of many years of effort to increase hardware reliability, particularly of critical components such as the kicker systems.[17] Expanded feedback control, improvements in the Machine Protection System, refinements in tuning procedures and better diagnostics all contributed. The Machine Protection System has been extensively upgraded with the most sensitive areas modified to be more robust. Wire scanners in the Injector, Linac, Final Focus and various transfer lines provide fast, precise, non-invasive measurement of the beam size to facilitate machine tuneup and to monitor routine operation. Operating efficiency in 1992 has been 60–70% with the total of scheduled and unscheduled downtime averaging less than 20% including interventions for the polarized source.

Feedback Systems

The most important single contribution to efficiency was undoubtedly the new generation of pulse-to-pulse feedback for orbit and energy control throughout the SLC.[11] Position and angle controls were implemented in more than twenty locations by the end of 1991, with another dozen loops added in 1992. The feedback systems have continued to be improved and extended to enhance machine stability. New feedbacks have been added for the polarized source and to control the beam trajectory into the Arcs. The sequence of orbit feedback loops down the Linac have been upgraded so that each loop receives information about incoming disturbances from its next upstream neighbor.[18] Each loop only corrects for disturbances not seen by the preceding loop. This eliminates the problem of multiple loops attempting to correct for the same disturbance and allows stable operation with faster response time. The loops also adaptively "learn" the transfer matrix from the upstream loop to compensate for possible drifts in the optics over several hundred meters of Linac.

Luminosity

Both the SLC luminosity and the efficiency for delivering luminosity to the SLD have improved steadily over the course of the 1992 run. During the March unpolarized run, the luminosity was a factor of 2 higher than in 1991. Initial running with the polarized source was at somewhat lower luminosity while optimal running parameters were found. The luminosity increased by a factor of 2 each month (Table 2) and by mid-August over 10,000 Zs had been logged by SLD with a polarization of 23%. Efficiency for logging events improved steadily with a more mature detector, improved trigger algorithms, and better control of backgrounds. Factors contributing to the SLD/SLC ratio are well understood. The SLC luminosity delivered is only 80–85% of the estimated value due to missing pulses and beam tuning. SLD downtime and deadtime contribute another factor of 80–85%, for an overall efficiency of 65–70% by the end of the run.

Table 2. Luminosity delivered during 1991 and 1992 runs.

	SLC Estimated	SLD on Tape	Ratio
1991	1500	330	22%
March	2900	1000	35%
May	2000	1000	50%
June	4000	2200	55%
July	7000	4500	67%
August 1–15	3800	2600	69%

Future Plans

The goals for the 1992 run were to deliver an integrated luminosity of 10,000 polarized Zs for the SLD and to reach a rate of 50–100,000 Zs per year. The integrated luminosity goal was reached on August 15 (Figure 2). The last month of running will concentrate on raising the peak luminosity by another factor of 1.5–2 and on testing higher polarization. For the 1993–94 run, SLD should integrate 10^5 events with a polarization of > 40%.

Acknowledgments

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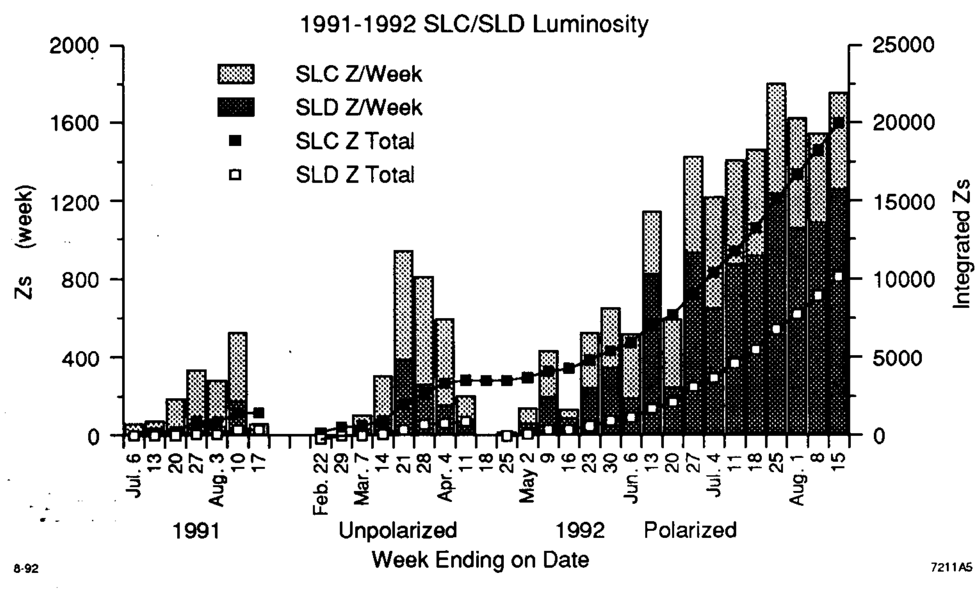

Fig. 2. Plot of luminosity per week and integrated luminosity for the 1991–1992 runs.

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