STATUS OF THE SLC – DEVELOPMENTS IN LINEAR COLLIDER PHYSICS*

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Introduction

This paper reviews the performance of the SLAC Linear Collider, both from the perspective of a machine delivering high luminosity polarized beams for physics, and as a test bed for future linear colliders. The development of the SLC has taken place over a number of years and the steady improvements have been documented in previous review papers such as reference[1]. As a review paper, the list of references also serves as a bibliography, pointing to the work of the many people contributing to the upgrades and commissioning of the various SLC systems.

The major upgrades for this present run have been an improved final focus optics, new low impedance vacuum chambers for the damping rings and improved polarization from the electron source.

The performance of the SLC is driven to some extent by its unique 3-beam operation in which the linac accelerates both the electron and positron bunches for collision, as well as the electron bunch to produce the positrons. The special attention required to maintain stable operation in the face of the interactions caused by beam loading from the bunches will (fortunately!) not be an issue in future linear colliders. They will deal instead with the problems associated with handling long bunch trains.

Luminosity and Polarization Performance

The SLC luminosity is traditionally measured in units of Z° particle production at the energy of the Z° mass. The weekly integrated luminosity measured in units of Z° recorded by the SLD experiment is shown in Figure 1 for runs since 1992.

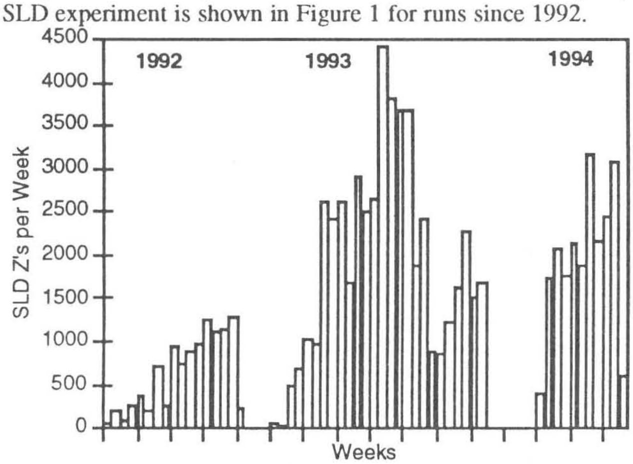

Figure 1: SLC Luminosity History

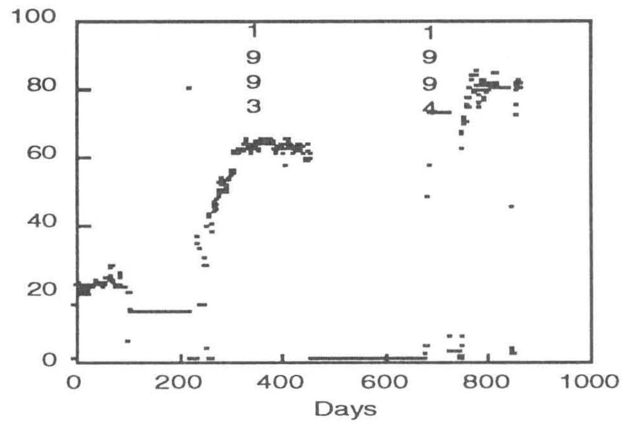

Figure 2: SLC Polarization History

Polarized beam operation began in 1992 when a beam polarization of 22% was achieved at the Interaction Point (IP). In Figure 2 it can be seen that the polarization rose to 63% in 1993 and has now reached 80% in 1994.

The machine availability, or up-time over this same period is shown in Figure 3. The impressive 70% average up-time in 1993 contributed greatly to the integrated luminosity of the run. The up-time is significant not only in terms of the number of hours that the beams are in collision, but also for providing steady conditions for optimal tuning of the beam. In a single pass collider, where each pulse can potentially have a different orbit and emittance, many machine parameters must converge to their optimum values before the peak luminosity is achieved. This requires extended periods of stable operation without interruption by hardware failures.

Interplay of Luminosity Parameters

The luminosity at the IP is related to the beam size, its intensity and repetition rate by the following equation:

$$\int Luminosity = \frac{N_{e^-} N_{e^+}}{4\pi\Sigma_x\Sigma_y} \times f_{rep} \times uptime \times BackgroundQuality$$

This is the useful, integrated luminosity recorded by the detector and contains a factor for the up-time of the machine as well as a factor for the detector background quality. The latter factor indicates whether the luminosity events can be discriminated in the detector. Optimizing the luminosity involves complex trade-offs between the beam parameters at the IP.

The bunch intensities N_{e-} and N_{e+} are raised subject to direct limitations, such as in the damping rings where there are

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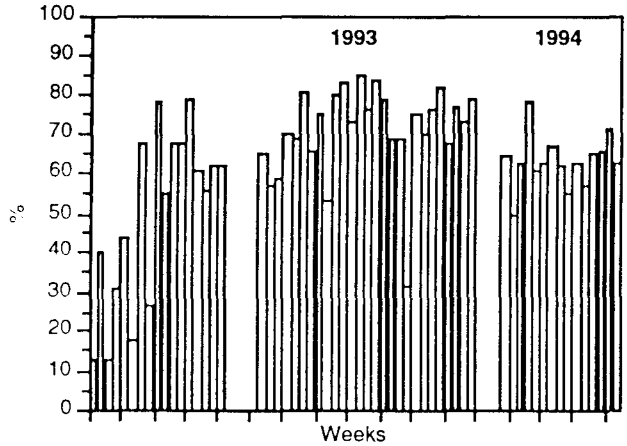

Figure 3: SLC Up-Time History

distinct intensity thresholds for various instability phenomena. The overlapping spot sizes Σ_x and Σ_y are determined by the optical properties of the final focus and by the emittance of the beams. The emittance growth due to wakefield effects imposes an indirect limit on the beam intensity. However, at some point an increase in intensity can also cause significant disruption in the colliding beams such that the luminosity is enhanced by the focusing of one beam by the other. The enhancement is linearly dependent on the bunch length at the IP, but the choice of bunch length and corresponding energy spread also has consequences for the emittance preservation in the linac. The energy spread increases the damping mechanisms that counter the effects of wakefields, discussed in subsequent sections, but is detrimental for both the chromatic contribution to emittance growth in the linac and the chromatic aberrations in the final focus.

The repetition rate is largely cast into the technological design of the collider and its power limitations. There remains some interplay with the beam parameters via the choice of time available between beam pulses in which the next bunch is damped in the damping rings, thereby influencing the emittance of the bunch injected into the linac. Synchronization of the accelerator cycles only allows us to vary this parameter in coarse steps of 1/120th of a second.

The up-time factor cannot be predetermined with any great precision. We have a general knowledge that tolerances on various systems, such as power supplies, become tighter when stricter demands are placed on orbits, emittance growth and on the control of final focus aberrations. Higher intensities also place greater demand on systems such as the damping ring vacuum chambers where beam heating and ion effects play a role. Around collimation sections in the collider there are correlations between the beam-loss dose and the mean time between failures for some critical components such as pulsed magnets. Statistics are difficult to interpret as we continually push the performance envelope of the SLC. Planning the appropriate preventative maintenance for optimum reliability is subject to continuous review at SLAC.

The up-time of the collider is also determined by the tuning time in each of the subsystems to arrive at low emittance beams and optimally focused spots. Beam stability is a prerequisite for any tuning algorithm to converge. Since stability becomes more difficult with increasing beam intensity, there is a necessary trade-off in operating intensity between integrated luminosity, achieved over several days, versus peak luminosity achieved on the time scale of an hour. The stability of the machine is further subdivided into long-term drifts in machine settings and pulse-to-pulse variations in beam parameters that we refer to as jitter.

The final factor in the luminosity equation is a quality factor for the background levels in the detector. It, too, constrains the intensities, emittances and final demagnification (or β^*) at the final focus by imposing limits on the angular divergence of the beam at the IP. Stability and jitter also play a key role in this background quality factor as the beam must remain centered in the collimation systems. If a beam tail or beam halo moves around and occasionally intercepts a collimator jaw the resulting shower can trip the detector off. It is even problematic if the beam tail takes an aberrant orbit through the final quadrupoles at the IP and generates synchrotron radiation that then intercepts the detector.

Table 1

Nominal SLC Operating Parameters for 1994

Intensity	N_{e-}	$[\mathrm{x}10^{10}]$	3.5
	N_{e+}		3.5
IP Geometric Emittance	ε_x	[µ µrad]	700
	ε_y		100
Overlapping spot size	Σ_x	[µ]	3.5
	Σ_y		1.3
Repetition frequency	f	[Hz]	120
Luminosity	L	[Z's per hour]	55

To trace the development of the SLC is to trace a complex curve in a multi-parameter space. The present operating parameter set in Table 1 exploits flat beam emittances [2], and incorporates a trend of increasing beam intensities as we learn to control different factors contributing to beam stability. The overlapping spot sizes reflect both improvements in final focus optics and beam emittance preservation.

SLC Subsystems

Polarized Electron Source

Remarkable developments in polarized electron source technology at SLAC have resulted in an increase in the level of polarization, evidenced in Figure 2. A detailed description of the source, which features a strained gallium-arsenide cathode, is found in ref. [3]. It is noteworthy that this level of polarization has been achieved at the moderately high intensity of $3.5\mathrm{x}10^{10}$ at the IP. This is only possible through the simultaneous high polarization and high quantum efficiency of around 0.25% at the cathode. The quantum efficiency is maintained by cesium activation that is performed on an approximate 5 day cycle. In anticipation of the future demand for an even higher intensity polarized source, a gun has been developed with a large-area cathode to deliver the same polarization with higher currents.

Damping Rings

Emittance Issues The damping ring emittance can be considered in the context of the total emittance budget of the collider. The emittance budget is the contribution to emittance growth along each part of the machine. The damping ring sets the initial minimum emittance before the emittance dilution in the linac and beam delivery system. When the emittances are optimally tuned throughout the system, as shown in Figure 4, the additive contributions from the downstream systems dominate the ring emittance. The picture is very different when the machine is not optimally tuned. Mismatches between the ring and the damping ring, for example, can introduce a very large emittance blowup. The Ring-to-Linac beamline (RTL) is very sensitive to optical errors because of the large discontinuity between the tight-focusing ring lattice and the linac lattice with its lesser quadrupole fill factor. The large energy spread introduced into the RTL by the bunch compressor means that much tuning effort is also devoted to correcting chromatic and dispersive effects [4].

The damping ring emittances have been extensively studied, especially with regard to producing flat beams with the lowest possible vertical emittance. The electron ring has half the store time of the positron ring so the actual damping time value is more critical for electrons. Damping times are measured with a gated camera looking at the synchrotron light image from the ring [5]. It was possible to improve the horizontal damping time in the electron ring by increasing the horizontal damping partition number, by stretching the ring circumference a total of 8 millimeters without compromising the ring acceptance.

High intensity effects in the beam emittance behavior are still under investigation in the damping rings. The effects are more pronounced in the electron ring which led to a concern over ion effects, but no corroborating evidence for this has been found.

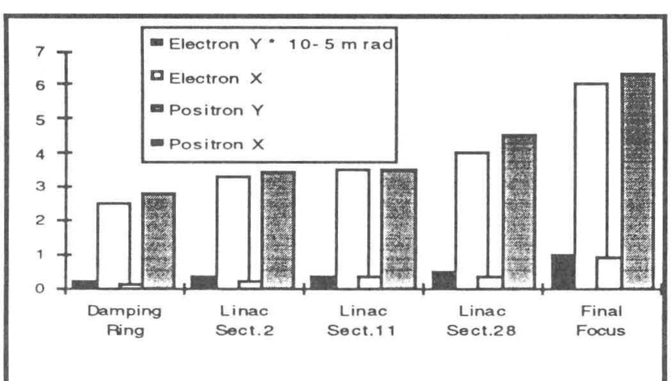

Figure 4: SLC Normalized Emittance Budget

Intensity Issues The primary issue for the damping rings has not been emittance, but beam stability as the intensity is raised. A single bunch instability, dubbed the sawtooth instability [6], was the major intensity limitation for the SLC up until 1993. This bunch length instability is driven by the broadband impedance of the vacuum chamber. A new, low-impedance vacuum chamber was installed in the arc sections of both rings during the 1993-94 downtime.

The old vacuum chamber had a sharp threshold at $3x10^{10}$ particles per bunch, above which the sawtooth would cause jumps in the relative bunch phase at injection into the linac, producing so-called flier pulses. Aberrant orbits of flier pulses can trip the machine protection system for the detector or the accelerator. The new vacuum chamber has a single bunch instability threshold that is actually lower at $2.3x10^{10}$, but the instability amplitude is much lower and does not appear to generate flier pulses in the linac. The exact nature of beam jitter as the intensity is raised is still being studied.

The onset of the single bunch instability is accompanied by an increase in the energy spread which can be measured in the profile of the extracted beam at a high dispersion location in the RTL beam line. These measurements confirm the observed sawtooth threshold at $2.3x10^{10}$ [7]. The threshold increases if the ring RF voltage is lowered, as a result of the longer equilibrium bunch length and lower synchrotron tune. However, the RMS beam jitter observed in the linac does not decrease as the ring RF voltage is lowered.

At high currents the beam loading also becomes an issue for the damping ring RF system. Lowering the RF voltage to counter the sawtooth threshold unfavorably lowers the ratio of cavity klystron power to cavity beam power, bringing the beam closer to the beam loading stability limit. At low RF voltages the beam loading transient at injection is particularly worrisome. The beam loading ratio is favorably restored by a direct RF feedback loop[8] which lowers the effective Q of the cavities as seen by the beam.

Linac

Emittance preservation and intensity limitations are inextricably linked in the linac. Beam orbit errors accumulating from the misalignments in the accelerating structures and in the quadrupole lattice cause the head of the bunch to generate transverse wakefields which deflect the rear of the bunch, producing tails in the transverse distribution of particles. The tails filament and the emittance of the bunch increases. The mechanism producing the tails is a resonant process in the sense that the wakefield kicks increase the amplitude of oscillation of the tail of the bunch if the whole bunch is oscillating at the betatron frequency. Consequently the most damaging misalignments are those with a component at the betatron wavelength.

Alignment has been steadily improved both through direct surveying techniques and through beam based methods of measurement. The linac is supported on a light pipe assembly whose alignment is controlled by a fresnel lens at the start of each 40 foot girder section[9]. Within each girder the alignment is checked optically at the quarter point supports, while maintaining stable thermal conditions[10]. The optical tooling technique has more recently included the relative alignment of the accelerating structure with respect to the girder, with a 150 micron precision. Some of the largest alignment errors caught this way have been at the ends of girders containing an instrumentation section where the accelerating structure is omitted. The quadrupoles had been aligned using beam based methods in these regions, but in some locations the alignment corrections are compensating for a tunnel subsidence. The result is that the quadrupoles had been progressively moved in one direction while the support girder had been left behind.

The beam based alignment method[11] fits the orbit of both the positron and electron beams. The two-beam orbit fitting solves for both the quadrupole alignment offset and that of the Beam Position Monitors (BPMS). Using this technique the linac quadrupoles and BPMS are now aligned to a common axis with an RMS error of about 100 microns.

This beam based technique does not reveal misalignments in the accelerating structure itself so we have relied on optical surveying techniques. However, there have recently been experiments with measuring the transverse waveguide modes in the structures that are excited by an off axis beam. Instrumentation was added to both the input and output waveguide couplers to look for signatures of the dipole mode at around 1.5 times the fundamental accelerating mode frequency[12]. Clear signals could be discriminated in both the frequency and time domain, but as yet this technique has not been used for practical alignment purposes. It would appear to be a useful diagnostic for future linear colliders when couplers can be incorporated in the original design.

Emittance bumps are used as a tuning technique[13] to compensate for wakefield induced emittance growth. An orbit oscillation can be created whose phase and amplitude just compensate the component of a local misalignment at its betatron wavelength. The oscillation is ideally placed to locally cancel any misalignments. In practice the orbit oscillations, made independently in each plane, extend over several sectors of the linac and their phase and amplitude are empirically adjusted to minimize the emittance at the end of each region. Such orbit bumps are only successful if their amplitudes remain less than a few hundred microns.

Large amplitude orbit bumps are an indication that large errors are being compensated. The phase of both the wakefield generating term and the compensation term are sensitive to the energy profile in the linac. Unavoidable local energy fluctuations perturb these phases resulting in incomplete cancellation of wakefields and a beam tail appears that changes from pulse to pulse, contributing to beam jitter.

Introducing an energy spread into the beam decoheres the wakefield-induced oscillations of the tail of the bunch. This is the basis of the BNS damping [14]applied to reduce the effects of jitter. The energy spread is introduced by offsetting the phase of the bunch by -22^{o} from the crest in sectors 2 through 8 and then reducing it to zero by making it +16^{o} in the remaining sectors 9 through 30. This phase profile gives an energy spread reaching a maximum of 2.2% in the linac[15]. Choosing a stronger BNS phase would dampen jitter effects further but introduces an unacceptable level of emittance growth through chromaticity and dispersion.

The emittance dilution from the chromatic focusing of the quadrupoles increases with both the energy spread and the betatron tune of the lattice. Dispersion is generated in the quadrupoles by misalignments and orbit bumps (another reason for keeping the emittance bumps small). A method of dispersion free steering has been studied at the SLC to reduce this contribution to emittance growth[16].

Controls and Feedback Systems

The SLC control system has matured beyond merely setting and reading hardware parameters. It corrects beam parameters, monitors the short and long term stability of the beam, and enables orthogonal tuning of beam parameters through simultaneous control of multiple hardware parameters. This level of sophistication is largely due to the implementation of feedback loops throughout the machine[17]. Beam intensity, beam energy and beam orbits are under servo control at key locations in the machine. Launch parameters are controlled, for example, at the boundaries between SLC subsystems. Tuning of the emittance bumps referred to in the previous section is only possible through the use of orbit control feedbacks along the length of the linac.

Orbit control loops are placed every few sectors along the linac to correct not only launch errors coming out of the damping ring into the linac, but also errors introduced along the linac from power supplies or mechanical motion. The effectiveness of several loops working in consort to control the orbit along the length of the linac, can be improved by a cascade system[18]. The cascade passes information from one loop to the next as to what error was detected upstream so that not all loops try to correct it at once. An orbit oscillation should be corrected by only the first loop where it is detected , otherwise downstream loops will overcompensate and introduce new oscillations in the process. The effectiveness of the cascade is limited by the accuracy of the knowledge of the phase advance of the orbit oscillations from one loop to the next. The phase advance along the linac is frequently perturbed by local changes in the energy profile along the linac, as the complement of the klystron tube population changes. An essential part of the cascade process is to make it adaptive to these changes by continually updating its own measured value of this phase advance between loops. The ever present low-level orbit jitter is sufficient for the control system to calibrate the phase advance along the linac.

Beam Delivery and Final Focus

The Arc synchrotron radiation emittance contribution is now the largest residual emittance term after optimal tuning, as shown in Figure 4. Standard tuning techniques are now well established to control the betatron coupling in the arcs that stems from the use of rolled combined function dipoles[19]. The coupling and betatron mismatch had previously been a dominant source of emittance blowup. More recently, attention has been turned to the spin transport properties of the arcs[20] and the possible depolarization effects caused by orbit errors and energy spread. Vertical orbit errors cause the spin to precess many times along the length of the arc. The exact number of precessions depends strongly on the energy of the particles. An energy spread in the bunch will result in some depolarization, or worse, produce a correlation between the particle energy and its polarization. An early outcome of the spin transport studies was that it was possible to use the arc as a spin rotator and forgo the use of the solenoid spin rotators at the exit of the damping rings. A consequence for the SLC of turning off these solenoids is the relative ease with which flat beam emittances can now be produced. The spin orientation at the IP is instead controlled by introducing vertical orbit bumps [20] along the arc. These spin bumps are now being refined to minimize the total spin precession number for the arc to reduce the spin-energy correlation.

The Final Focus (FF) was upgraded during the last downtime to improve the diagnostic capabilities, the tunability and reduce the aberrations in the optics. Wire scanners have been added to the FF beamline to enable more precise measurement of the emittance[21], thereby helping to resolve questions such as which beam contributes at any given time the most toward the overlapping spot size at the IP and also what the emittance contribution is from the arcs. Since the spot size is too small for a wire scanner to survive at the IP, one of these scanners is located at an intermediate waist which is a magnified image of the IP. Even magnified, the vertical beam size is less than 5 microns and presents a technological challenge for the scanner.

The intermediate waist wire scan facilitates a more orthogonal control of the beta match in the FF. Previously, the beta match was made at the IP and involved a perturbation to the final triplet and so upset the chromatic correction. With the addition of quadrupoles to the upper transformer the beta match is now done at the intermediate waist, leaving the final triplet and chromatic correction untouched[22]. Further tuning improvements include the addition of trim quadrupoles to the chromatic correction section to zero the dispersion at the IP.

The new FF design reduces a significant aberration at the IP that is generated by the interleaving of the x- chromaticity and y-chromaticity correction sextupoles in the original design. A correction quadrupole was installed $\pi/2$ in phase upstream of the final triplet which acts to cancel this $y'^2\delta^2$ aberration (U_{3466} in TRANSPORT notation)[23]. This correction should allow the aberration limited vertical spot size to be reduced to about 2/3 of its previous value, giving an effective β_y^* of around 2.0 mm. At low currents vertical spot sizes of 420 nm have already been achieved, doubling the normalized luminosity over the previous year's value.

Conclusion

The SLC continues to face new challenges as efforts are made to further increase the integrated luminosity by raising intensities and at the same time maintaining stable beam conditions for optimum spot size tuning. The experience gained in emittance preservation and the integrated role the control system plays in beam tuning have great bearing on future linear colliders.

Acknowledgments

In addition to the many SLC physicists referenced in this paper contributing to the improvements in machine performance and understanding, a deserving acknowledgment is made to the operations and support staff at SLAC for their efforts.

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