RECENT SLC DEVELOPMENTS

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Abstract

The SLAC Linear Collider (SLC) is the forerunner of a new generation of high energy accelerators. As such, it incorporates many novel features that must be fully exploited to achieve optimum performance. In this paper we present an overview of the frontiers of collider performance at SLC. Recent developments have centered on polarization, intensity and emittance preservation issues. A polarized source and spin transport system were successfully commissioned in 1992 and operated with high reliability. Practical intensity limits associated with rapid growth ($<\tau_s$) bunch length instabilities have been observed in the damping rings. Ring RF voltage manipulations are used to suppress the instabilities. Emittance preservation technique development has focused on controlling system-wide instabilities and improving feedback and tuning procedures. Control of instabilities of all time scales, pulse to pulse, fast and slow, is one of the most challenging aspects of the collider. The challenge is met with 1) very high level of control and automation required for general tuning and optimization, 2) real-time transport line optical correction and monitoring, 3) coupled, high level, trajectory and energy feedback, 4) high order multipole optical correction and monitoring, 5) feedback-based linac beam emittance preservation, and 6) interaction region luminosity optimization. The common thread beneath all of these is the SLC control system which must provide a level of control, diagnosis and feedback not required for simpler machines.

I. Introduction

The novel features incorporated in linear colliders are the small beam size at the interaction point and the low repetition rate which for SLC are about 1μm and 120Hz. Table 1 shows some typical SLC operating parameters.

The challenges for the linear collider are: 1) produce the high intensity bunches, 2) preserve their emittance throughout the system, 3) produce the aberration-free spots at the interaction point and 4) control instabilities. At SLC there are the additional challenges of polarized beam production and transport. Other luminosity related topics such as repetition rate, detector backgrounds and system reliability will not be discussed in this paper[1].

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Parameter	1992	1993	Design (1985)
Energy (GeV)	45.6	45.6	50
Intensity (10^{10})	3.0	3.2	7.2
Polarization (%)	24	60	-
Linac Emittance ($\gamma\epsilon$, 10^{-5} m-rad)	3.5 x 3.5	4 (x) 0.7 (y)	3
Interaction Point beam size (μm)	2.1(x) x 1.7 (y)	2.3 x 0.7	1.7 x 1.7
σ_z(mm)	1	1	1.5
σ_E/E (% rms)	.3	.3	.25
Luminosity (10^{29} cm^{-1} s^{-2})	2.4	3.6	60
Luminosity (Z events/hr)	26	40	650
Enhancement from disruption		~1.1	2.2
Rep. rate (Hz)	120	120	180

Table 1. SLC Beam parameters at the interaction point, (except where specified).

II. Review of Performance

The design luminosity of the SLC with 7.2 x 10^{10} per bunch and 180 Hz operation is 6 x 10^{30} cm^{-1} s^{-2}. The design estimates also included a factor of 2.2 for disruption which is expected to be 1.1 at the lower currents. The design luminosity calculated for 1993 intensities and repetition rate is 4 x 10^{29}. Present peak performance is 40 Z_0 events per hour or approximately 3.6 x 10^{29} cm^{-1} s^{-2}. Typical average luminosity, (neglecting downtime) is about 80% of that, or 32 Z_0 per hour.

The first collisions involving polarized electrons occurred in April 1992. At that time, a large, unanticipated, spin precession was observed in the arcs. The cause is the fact that the arc vertical betatron tune and spin tune are close enough to one another to be in resonance. While the spin resonance introduces some depolarization (about 15% relative), it can be used with benefit for spin direction manipulation using vertical trajectory bumps[2]. A

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fortunate side effect of this is that it allows the spin rotators at the ring exit and linac entrance to be powered off. Since the superconducting rotator solenoids introduced significant x-y coupling (which was harmless if the beams were round ($\varepsilon_x=\varepsilon_y$)), disconnecting them made it easier to transport damping ring flat ($\varepsilon_y<\varepsilon_x$) beams to the linac.

Emittance dilution occurs more strongly in the horizontal plane so the flat beam spot area at the IP is significantly reduced. Flat beams also facilitate the operation of the vertical final triplet focusing at the optimum between the linear and higher order aberrations. With round beams this is difficult due to the detector background generated in the final triplet. Flat beam operation has provided a gain of 1.5 in luminosity. The beam size reduction in the final triplet has also significantly reduced the detector's sensitivity to backgrounds.

Goals set for the 1993 operating cycle (1/1 - 9/1) include 50K Z_0 events recorded on tape with a polarization of greater than 40%. Early in the cycle, the polarized electron source[3], using a strained lattice GaAs photocathode, achieved much higher polarization. Typical polarization at the IP is greater than 60%. The luminosity performance is also good, with an average of about 500 Z_0 delivered per day. With some improvements expected during the cycle from improved feedback and tuning procedures, our goals should be surpassed by a good margin.

III. Intensity

Intensity limitations come from a charge limit effect of the polarized source and single bunch longitudinal instabilities[4] in the damping ring. Because of these two effects, prolonged operation at intensities higher than 3.5 x 10^{10} has not been done in the linac and positron system.

Soon after the polarized electron photocathode gun was tested online in late 1991, a 'charge limit' effect was discovered that limits the single bunch charge that can be extracted from the gallium arsenide photocathode in a 2 ns full width pulse[5]. The limit is proportional to the low laser light quantum efficiency and the resulting saturation has the benefit of reducing the impact that laser light intensity instability has on the electron beam operation. Testing is proceeding on a gun with twice the cathode area which should provide more than 5 x 10^{10} in the damping ring.

A practical limit to the present damping ring intensity is the observed bunch lengthening instability which occurs at a threshold of 3.0 x 10^{10} in each bunch. The onset of this instability is marked by a phase error of the bunch at extraction from the ring. The errant bunch is not properly longitudinally compressed and therefore does not propagate through the linac to 47 GeV with the proper phase space volume. The associated losses usually provoke a response from the beam loss power limiting protection system which forces a momentary 4 second shut down. Production running is effectively stopped if this occurs too often.

The cause of the instability is the high impedance of the damping ring vacuum chamber[6] which has a computed inductance of 37.5nH. By reducing the RF voltage with a slow ramp after injection and restoring it before extraction, the peak bunch current is decreased during the damping cycle. The generator gap voltage is reduced a factor of 4 requiring the use of a wide bandwidth feedback to maintain centroid stability[7]. In order to compensate for the small bunch lengthening that results after the ramp completes, the extracted bunch can be shortened using timed RF voltage pulses just before extraction[8]. With this technique, the onset of the instability can be prevented up to intensities of about 4 x 10^{10}.

The positron source operates at the design yield of one damped positron per incident 30GeV electron on the positron target. The yield of 150 MeV positrons from the target is 4. The large losses throughout the positron transport and damping ring are accompanied by intensity instabilities of typically 3 to 6% at the output of the damping ring. Efforts are underway to identify the instabilities that cause the increase in relative intensity jitter from the target to the damping ring exit.

IV. Emittance Preservation

Emittance or spot size issues have been addressed successfully. With the flat beam operation, first tested in 1992 and implemented in 1993, the normalized luminosity, (L/N^+N^-), has surpassed the design with vertical IP beam sizes as low as 800nm. Emittance issues involve all systems downstream and including the damping rings. The phase space orientation and coupling in the arcs and final focus must also be controlled and corrected.

In the last two years the performance of each SLC subsystem has been improved through the widespread use of phase space monitors and careful application of transfer function mapping techniques[9]. For each SLC subsystem automated or semi-automated emittance control and tuning procedures have been implemented.

Damping ring studies done in 1991 showed a significant dependence of the damping time on the tune[10] leading to a 20% increase in the extracted emittance for a 0.1 change in the tune. Studies showed the probable cause to be related to alignment effects. As a result of these studies, the ring radius was changed, reducing the transverse partition numbers at the expense of an increase in the longitudinal partition number. The electron ring damping time was reduced 10% from 3.8 to 3.4 ms.

Optical tuning techniques are required due to the tight alignment tolerances placed on items such as the chromatic correction sextupole magnets and the linac disk loaded waveguide. These techniques have been developed and automated where typical time constants make it necessary. Examples of these are: 1) Linac emittance tuning using orbit bumps, 2) Higher order optical tuning in the ring to linac bunch compressor using phase space monitors, 3) Arc coupling and emittance growth tuning using transfer function grid maps, 4) Final Focus dispersion correction using phase space monitors[11], and 5) Final Focus sextupole alignment correction using bumps and beam size monitors[12].

Items 1) and 3) from the list above are important since they allowed flat beam operation[13]. In the linac, wire scanner emittance measurements made at 1.2, 15 and 47GeV provide information used to correct beam tail and emittance growth coming from residual dispersion and transverse wakefields[14]. Typical trajectory oscillation amplitudes used for the correction are 100 to 200μm. The fast steering feedback loops used throughout the linac are used to maintain the bumps to the ±15μm level. At nominal operating intensities, emittance growth can be kept below 50%. Normalized emittances as low as 1.5 x 10^{-6} m-rad have been observed at low intensities (10^{10}).

Grid mapping techniques have been used for controlling the phase space transformation in the arcs for several years[15]. During the 1993 start-up, this technique was used to reduce cross plane coupling to levels acceptable for flat beam operation.

V. Interaction Region Optimization

The most extreme application of automated tuning is found in the IP spot size optimization. Waist, skew, dispersion and chromatic correction scans are used for testing and making corrections for slow drifts of the incoming beam parameters and for changes in the performance of the final focus correction systems. Among new items for 1993 are the special handling of the flat beam-beam deflection fit[16] and the implementation of a radiative Bhabha pulse to pulse luminosity monitor. The latter device has proven to be a useful check on the luminosity estimated from the beam beam deflection fits and a valuable indicator of short time scale instabilities.

VI. Stability Control

It is perhaps improvements in the control of instabilities of all sorts that have made the most contribution to the good performance of the last two years[17]. Table 2 shows a rough categorization of collider instabilities, categorized both by their time scales and the response they evoke.

Clearly the goals, as broadly indicated in table 2, are to 1) directly fix or control pulse to pulse instabilities using techniques tailored to the problem, 2) move as many as possible into the 'fast' category and 3) build control system tools and mechanical protection for beam power related instabilities. The underlying key to dealing with these issues is a very strong control system which provides the high level programming environment necessary for generating robust feedback and tuning tools.

The introduction, in 1992, of high level fast steering and energy feedback[18], has provided 5 important benefits to SLC operation: 1) operability (through rapid recovery from simple faults), 2) orthogonalization of beam parameters through calibrated fit of BPM data, 3) improvements over the single instrument resolution through constrained fits of many BPM's, 4) immunity from first order thermo-mechanical effects and 5) decoupling of upstream and downstream systems. The final item in the list may be the most significant since it allows fine optical optimization to proceed continuously without complications due to downstream centroid displacements. Several such tuning procedures are non- or minimally invasive and take place during routine operation.

The use of the feedback loops to orthogonalize and record beam parameters such as position, angle and energy has provided clues leading to the cause of slow instabilities. In many cases tunnel air temperature stabilization has made a significant improvement. In addition to recording the centroid value and correction required for stabilization, the feedback loops also record the pulse to pulse stability or the rms variance of each parameter. The stability record provides a similar tool for tracking down sources of pulse to pulse instabilities. By using this and related techniques, linac disk loaded waveguide girder vibrations were identified in early 1992. The 2μm vibrations were reduced by a factor of 20 using simple support struts[19].

VII. Planned Improvements

Two major upgrades are planned for the coming SLC downtime; 1) a new, low impedance damping ring arc vacuum chamber and 2) a major final focus optics upgrade that will reduce remaining aberrations and provide tuning diagnostics.

The new vacuum chamber will have an inductance that is 7 times lower than the present one. It will be built using novel wire electro-discharge machining (EDM) construction techniques and will have a greatly reduced number of flexible bellows. In order to accommodate the rigid chamber, a clearance between the chamber and the quad and bend magnet poles of ±1 mm has been introduced. This requires the installation of separate vacuum chamber and BPM supports and also requires an upgrade of the existing magnet supports. This improvement should put the microwave single bunch instability safely out of reach of other practical limits.

The final focus optics upgrade addresses residual third order aberrations of the system. For this project a single, high field quad will be placed at the closest waist to the IP. This quad will eliminate the largest remaining aberration. Octupoles are also planned which will allow the generation of 320nm vertical spot sizes at the IP with present emittances. The introduction of these elements tightens the tolerances and the tunability of the final telescope. In order to stabilize the optics of the final telescope as well as provide more powerful tuning tools, six new wire scanners are planned per final focus.

These two upgrades have the potential to provide a fivefold luminosity increase.

VIII. Conclusion

The success of the SLC as a prototype of the next generation of electron positron colliders is striking. The number of papers and workshops dealing with linear collider accelerator physics has grown rapidly in the last 5 years and shows strong signs of continued growth. Most major accelerator laboratories worldwide now have large ongoing linear collider research and development programs. The SLC provides a unique laboratory for testing practical collider issues. Of the many challenges that face the next linear collider, perhaps none is more clearly illustrated at SLC than the need for an extremely powerful instrumentation and control system which can be used to perform tuning and feedback processes.

IX. Acknowledgments

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Class	Definition	Sources	Examples	Diagnostic
Pulse to pulse	Not amenable to beam based feedback - truly random process	Pulsed Devices (e.g. thyratron driven) Beam dynamics Vibration	Kicker Girder vibration Source	Synchronous pulse-coded data acquisition
Fast	Quickly detected and corrected with no interference	Power Converters Thermal Operator tuning	Power line phase synchronous	Fast feedback Optimized tuning procedure
Slow	Complex analysis requiring expert - fix is interfering	Ground settling Thermal Power Converters	Optics tuning RF phases	Dither control Synchronous acquisition
Rate	Beam power limiting machine protection system	Beam Dynamics Pulsed device breakdown	Klystron Fault	Trip driven snapshot Data acquisition traps

Table 2. Table of linear collider instabilities and examples. Instability classifications are determined in part by the rate with which the problem can be cured. Synchronous data acquisition techniques, whereby data from diverse monitors throughout the complex are taken on the same or related pulses, is an powerful tool for the diagnosis of instabilities.

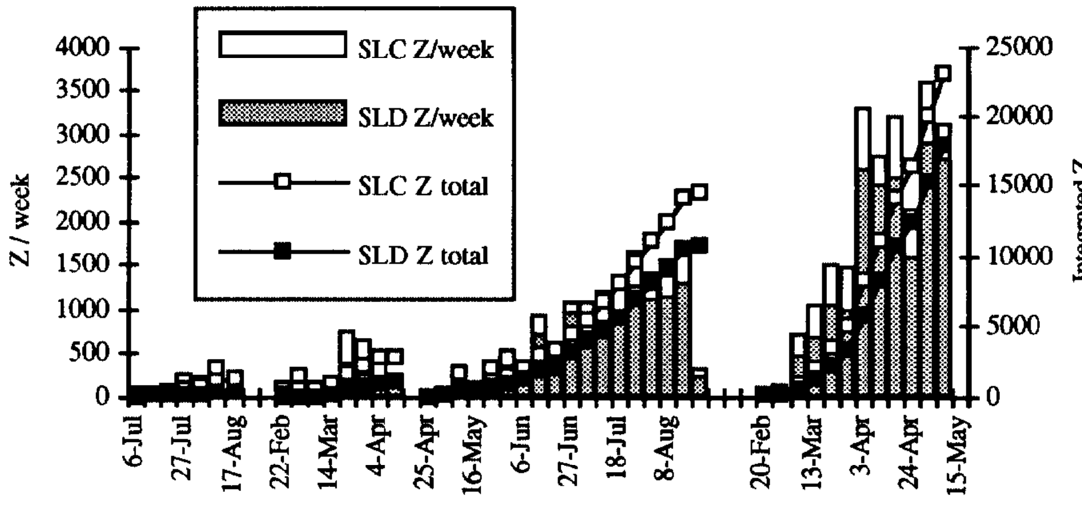

Figure 1. SLC Performance from 1991 to mid-May 1993. The left hand scale is in Z/week and the right hand scale is total integrated Z's delivered. SLC Z's are projected from luminosity monitors and SLD Z's are actually identified events.

X. References

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