NEW TECHNIQUES FOR EMITTANCE TUNING IN THE SLC*

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Abstract

In the 1997-98 run, the luminosity of the SLAC Linear Collider (SLC) increased by about a factor of four compared to previous runs. A significant contribution to this improvement came from revised emittance tuning techniques throughout the accelerator. A new strategy was used to cancel wakefields and dispersion in the LINAC. Careful monitoring and control of the ARCs optic reduced the emittance growth due to coupling, wakefields and synchrotron radiation. New Final Focus optics and upgraded diagnostics improved the emittance measurement resolution and otpimization. These and other new procedures resulted in an average 25residual emittance growth in both planes from the damping rings to the interaction point.

1 LUMINOSITY OVERVIEW

During the 1997-98 run, a total of 350,000 Z^0s were recorded with an average electron beam polarization of 74%. This was nearly double the total sample of events from all previous SLD runs and reflected a substantial increase in luminosity of about a factor of four. The peak luminosity delivered was 300 Z^0s per hour or 3 10^{30} cm^{-2}s^{-1} with a record of more than 5300 Z^0 events recorded in 24 hours. The luminosity steadily increased throughout the run bringing the SLC to within a factor of two of design [1]. The improvement was due almost entirely to changes in tuning procedures and reconfiguration of existing hardware with no major upgrade projects.

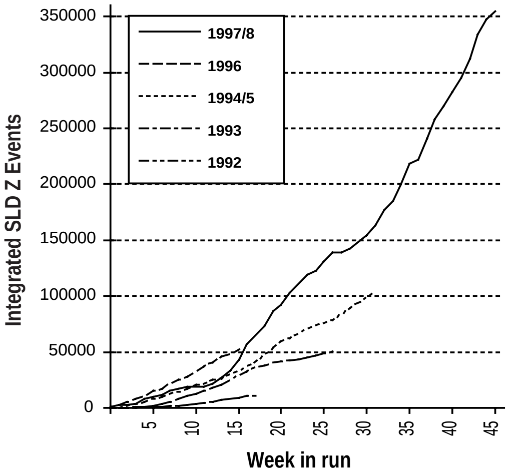

Figure 1: History of integrated SLD Z^0 events from 1992 through 1998, showing the steep increase in 1997-98.

The luminosity of a linear collider L is given by

$$L = \frac{N^+N^-f}{4\pi\sigma_x\sigma_y}H_d, \qquad (1)$$

where $N^\pm$ are the number of electrons and positrons at the interaction point (IP), f is the repetition frequency, $\sigma_{x,y}$ are the average horizontal (x) and vertical (y) beam sizes, and H_d is the disruption enhancement factor which depends on the beam intensities and on the transverse and longitudinal beam sizes. At the SLC, the repetition frequency is 120 Hz and the beam intensity is limited by wakefield effects and instabilities to about 4 10^{10} particles per bunch. The only route to significantly higher luminosity is by reducing the effective beam size. Using the definition of emittance as the product of the beam size and angular divergence ($\theta_{x,y}$), $\epsilon_{x,y} = \sigma_{x,y}\theta_{x,y}$, one may reexpress the luminosity as

$$L \propto \frac{\theta_x}{\epsilon_x}\frac{\theta_y}{\epsilon_y}H_d. \qquad (2)$$

For higher luminosity, the basic strategy was to decrease the emittance and increase the angular divergence. Any reduction in beam size strengthens the disruption, or mutual focusing of the beams, and further increases the luminosity.

2 EMITTANCE TRANSPORT

A variety of new techniques were used to minimize the emittance growth from the damping rings to the final focus. In the ring-to-linac transfer lines where the bunch length is compressed, the horizontal beam size is large and fills the available aperture, causing emittance dilution and beam loss. Ballistic beam-based alignment minimized dispersion generated in the strong matching quadrupoles. A new optics with a larger momentum compaction factor better matched the beam size to the apertures and reduced losses [2]. Shielding sleeves were also added to reduce wakefields generated by the bellows in the beamline.

In the linac, a new implementation of two-beam dispersion free steering [3] constrained the electron and positron beams to follow the same trajectory, minimizing dispersion and wakefields. Once established, the trajectories were stable over several months, with only occasional resteering required. A stronger focusing lattice [4] improved the damping of incoming oscillations while ensuring compatibility with PEP-II (the SLAC B-factory) operation. This also allowed a reduction in the beam energy spread introduced for BNS damping which helped minimize chromatic emittance growth. Known sources of jitter from vibrations in the mechanical systems near 10 Hz and in the water cooling systems near 59 Hz were reduced by stiffened supports, upgraded water pumps [5], and special high-speed feedbacks.

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Another important improvement was the development of a fast, accurate procedure for phasing the rf accelerating voltages. All of the 30 linac subboosters, each of which drives 8 klystrons, could be phased in about 2 minutes to an accuracy of 1-2 degrees. This provided a stable, well understood energy profile throughout the run [6].

In the collider arcs, emittance growth is inevitable due to the emission of synchrotron radiation in the bending dipoles. In addition, the non-planar geometry of these beamlines can cause transverse coupling. In this run, the optical properties of the arcs were more precisely optimized and maintained. First the beam trajectory was carefully centered through the magnets to reduce wakefields. Then the emittance growth was constantly monitored and minimized using refinements of the techniques first developed in 1990 [7]. The realization that the final focus dispersion matching quadrupoles strongly coupled the beam led to the development of new methods for matching dispersion in the arcs themselves.

Most importantly, the strategy for global optimization of the linac emittances was changed significantly. Since 1991, the SLC has used closed betatron oscillations early in the linac to cancel wakefield tails caused by residual structure misalignments [8]. Studies showed that where the energy spread is large, dispersion dominates the emittance growth. Oscillations used to cancel dispersion may generate additional wakefield tails. At low energy, the optics is also extremely sensitive to small errors in the energy profile. Tuning further downstream in the linac where the energy spread is small, produced more stable, reproducible results.

In previous runs, emittances were optimized using wire scanners located near the end of the linac at about the 90% point. Measurements in 1997 indicated that significant emittance growth can occur in the last 200 meters, as predicted by simulations [9]. The solution was to use wire scanners early in the final focus for the global optimization. To provide high precision measurements during luminosity running, several upgrades were required. Thin carbon wires were installed to allow measurements while the SLD detector was logging data. New optics improved the phase space coverage and high resolution (≈ 2 μm) beam position monitor electronics allowed precision correction for pulse-to-pulse orbit fluctuations. The revised optimization strategy produced not only a smaller emittance, but also much less variability without anomalous sources of emittance growth. Most significantly, for the first time, the emittance transport was qualitatively and quantitatively understood and controlled.

3 FINAL FOCUS IMPROVEMENTS

The key to improving the performance of the SLC final focus (FF) was the understanding that for non-Gaussian beam distributions, the beam sizes, $\sigma_{x,y}$, in Eq. 1 must be calculated from the integral over the beam overlap distributions and not from the root mean square (RMS) distribution. The upper curve in Fig. 2 shows the RMS beam size as a function of angular divergence for the 1996 FF optics. Because the RMS is dominated by tails containing only a small fraction of the beam, it increases after an optimum divergence value. The second curve shows the effective beam size when the integrals are properly evaluated and predicts higher luminosity for increased angular divergence. The third curve demonstrates the gains from a different FF optics used for this run where the final demagnification was moved closer to the interaction point (IP). With these optics, the divergence, beam size, and predicted disruption enhancement (assuming a 1 mm bunch length) were changed from $\theta_x = 350$ μrad, $\sigma_x = 2.0$ μm, $H_d = 1.3$ to $\theta_x = 470$ μrad, $\sigma_x = 1.5$ μm, $H_d = 2.0$. This was still less than the optimal values of $\theta_x = 530$ μrad, $\sigma_x = 1.3$ μm, and $H_d = 2.2$.

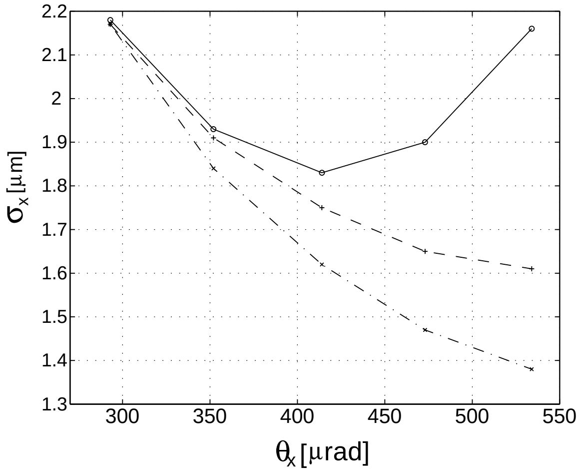

Figure 2: Horizontal beam size σ_y at the SLC IP as a function of angular divergence θ_y. Curves (solid), RMS, and (dashed), with proper integration, are for the 1996 optics. The dot-dashed is for 1997 optics.

At the SLC, the maximum achievable angular divergence is limited primarily by backgrounds in the SLD detector. In preparation for the 1997 run, changes were made to the FF collimation and to the masking near the IP. Collimators from the FF were moved to the arcs and rotated by 45° to allow for 'round' collimation. In addition, for most collimators ($\approx$60 jaws in total), a new technique ensured that they were properly centered on the beam to minimize wakefield kicks. Later, offline studies using upgraded tracking codes revealed that part of the detector backgrounds were generated by higher order chromatic terms ($\sim$ δ^2), specifically T_{266} and T_{226} in transport notation. Based on these results, permanent magnet sextupoles were installed just after the end of the linac and additional sextupoles were energized in the FF to cancel these contributions.

In addition to the new optics mentioned above, several other upgrades to the FF were implemented during the run to reduce the emittance growth due to synchrotron radiation and to cancel residual higher order aberrations. The additional FF sextupoles not only reduced backgrounds, but also reduced the contribution to the vertical beam size from two third-order aberrations, U_{3246} and U_{3244}, generated by the interleaved sextupoles. At the end of 1997, the average bend radius in the FF was increased by using offset quadrupoles and steering dipoles. This reduced synchrotron radiation emittance growth in both planes. In

February, permanent magnet octupoles were installed to further cancel the U_{3246} and U_{3244} vertical aberrations. The observed decrease in the vertical beam size was about 15%. Finally, in May the strength of the final quadrupole nearest the IP was increased to further raise the horizontal angular divergence. The horizontal and vertical beam sizes achieved were $\sigma_x = 1.5\ \mu$m and $\sigma_y = 0.65\ \mu$m, which together yield a beam area which is a factor of 3 smaller than the SLC design value.

4 LUMINOSITY OPTIMIZATION

To achieve and maintain the minimum beam size at the SLC IP, 5 final corrections are routinely optimized for each beam. These include centering of the x and y beam waist positions, zeroing of the dispersion η_x and η_y, and minimization of an $x-y$ coupling term. Since the first SLC collisions, an automated procedure has been used to scan the beam size as a function of each parameter and set the optimal value. The beam size was measured with a beam-beam deflection scan but this technique lacked the resolution required to measure micron-size, disrupted beams. It was estimated [10] that poor optimization caused a $20-30\%$ reduction in luminosity during the 1996 run. For 1997, a novel 'dithering' feedback was implemented which optimizes a direct measure of the luminosity (i.e. the beamstrahlung signal) as a function of small changes in each parameter [11]. By averaging over thousands of beam pulses, it was possible to improve the resolution by a factor of 10.

The feedback was configured to cycle through each of the 10 parameters automatically, typically every hour or two. In contrast, the old, slower, more invasive procedure was typically implemented only a few times per day. Because of the improved resolution, it was possible to align the FF sextupoles and new octupoles much more accurately and to develop new methods for cancelling all of the second order chromatic and geometric aberrations. An added benefit of the feedback optimization was that it was highly reproducible and no longer required operator intervention. Lastly, with the improved optimization and increased stability in the upstream systems, high luminosity was more quickly reestablished after any interruption.

5 DISRUPTION

In the 1997-98 SLC run, a significant luminosity enhancement from disruption was demonstrated for the first time. As the beams collide, each beam is focused by the field of the other beam, causing the transverse size to shrink. If the resultant focal length is shorter than the bunch length, the average beam size seen by the other beam decreases, which increases the luminosity. The magnitude of the disruption, or pinch effect, depends on the transverse beam size, the bunch length and the beam intensities. For this run, along with the significant reduction in beam size, the bunch length was carefully monitored and set to the optimum value [12]. In addition, the beam currents were maintained at record levels partly due to bunch precompression in the damping ring [13]. Fig. 3 shows the ratio of luminosity as recorded by SLD to that calculated from the measured beam parameters assuming rigid (i.e. undisrupted) beams. The data are in agreement with the theoretically calculated disruption enhancement. At the highest luminosity, the enhancement was more than 100%.

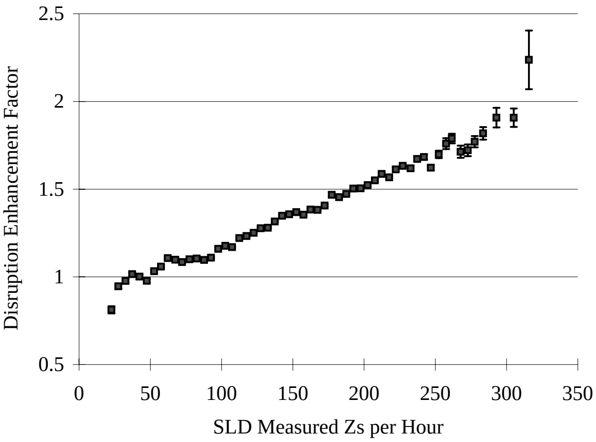

Figure 3: Ratio of luminosity measured by SLD to that calculated for rigid beams without disruption.

6 SUMMARY

The remarkable increase in luminosity after nearly a decade of operation demonstrates that the SLC remains on a steep learning curve and has far from exhausted its potential for further improvements and for a deeper understanding of linear colliders. The success of the 1997-98 SLD run was due to the hard work and dedication of many groups and individuals. In particular, we acknowledge the outstanding efforts of the operations crews and the engineering and maintenance staff as well as the physicists from SLD and the Accelerator Research departments.

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