SLAC–PUB–6118
May 1993
(A)

Flat Beams in the SLC*

C. Adolphsen, T. Barklow, D. Burke, F.-J. Decker, P. Emma, M. Hildreth, T. Himel, P. Krejcik, T. Limberg, M. Minty, N. Phinney, P. Raimondi, T. Raubenheimer, M. Ross, J. Seeman, R. Siemann, W. Spence, N. Walker, M. Woodley
Stanford Linear Accelerator Center
Stanford, California 94309

ABSTRACT

The Stanford Linear Collider was designed to operate with round beams [1]; horizontal and vertical emittance made equal in the damping rings. The main motivation was to facilitate the optical matching through beam lines with strong coupling elements like the solenoid spin rotator magnets and the SLC arcs.

Tests in 1992 showed that 'flat' beams with a vertical to horizontal emittance ratio of around 1/10 can be successfully delivered to the end of the linac [2]. Techniques developed to measure and control the coupling of the SLC arcs [3] allow these beams to be transported to the Interaction Point (IP). Before flat beams could be used for collisions with polarized electrons, a new method of rotating the electron spin orientation with vertical arc orbit bumps [4] had to be developed.

Early in the 1993 run, the SLC was switched to 'flat' beam operation. Within a short time the peak luminosity of the previous running cycle was reached and then surpassed. The average daily luminosity is now a factor of about two higher than the best achieved last year.

In the following we present an overview of the problems encountered and their solutions for different parts of the SLC.

I. FLAT BEAMS IN THE DAMPING RINGS

The SLC was designed to operate with 'round' beams where horizontal and vertical beam emittance are equal ($\varepsilon_x = \varepsilon_y$). Electron/positron storage rings naturally produce 'flat' beams where $\varepsilon_x >> \varepsilon_y$. Round beams had to be produced by operating the SLC damping rings on the linear coupling difference resonance:

$$\nu_x - \nu_y = n \qquad (1)$$

With round beams, the horizontal and vertical tunes in the electron and positron damping rings were $(\nu_x, \nu_y) = (8.28, 3.28)$ and $(\nu_x, \nu_y) = (8.18, 3.18)$. Alignment and field errors in the rings resulted in a resonance width of roughly $\Delta\nu \approx 0.01$. The normalized rms emittances were $\gamma\varepsilon_x \approx \gamma\varepsilon_y \approx 1.5\times10^{-5}$ m-rad.

To generate flat beams, the betatron coupling was reduced by separating the tunes by $\Delta\nu = 0.2$. The vertical dispersion due to residual errors was reduced by choosing the vertical tune close to half integer. Currently, the electron and positron rings are operating with horizontal and vertical tunes of (8.28,3.43) and (8.18,3.38), respectively. The difference between the electron and positron ring tunes is historical. For normal SLC operation, simply splitting the horizontal and vertical tunes is sufficient; producing beams with normalized rms emittances of $\gamma\varepsilon_x = 3\times10^{-5}$ m-rad and $\gamma\varepsilon_y = 0.3\times10^{-5}$ m-rad.

The vertical emittance could be reduced further with more sophisticated coupling and dispersion correction. However, in the electron damping ring, the beam is stored for only 2.4 damping times and thus the extracted vertical emittance is limited by the injected emittance. Emittance dilution in the bunch compressor after the damping rings, where the bunch length is compressed from roughly 10mm to 1mm, prevents the realization of significant improvements.

Further reduction of the vertical emittance was achieved during an experiment in 1992 where the electron damping ring was operated with a longer store time (and lower beam repetition rate). Vertical orbit bumps through the sextupoles were used to correct the betatron coupling and vertical orbit bumps in the insertion quadrupoles to correct the vertical dispersion. With these bumps, the vertical rms emittance was reduced to $\gamma\varepsilon_y \approx 0.05\times10^{-5}$ m-rad, a 1.7% emittance coupling ratio.

Under typical SLC operating conditions both the electron and positron vertical emittance at linac injection (after the bunch compressors) are $\gamma\varepsilon_y \approx 0.4\times10^{-5}$ m-rad. The horizontal emittances are $\gamma\varepsilon_x \approx 3.6\times10^{-5}$ m-rad. These values are quite stable with fluctuations primarily arising from orbit changes in the bunch compressor which generate vertical dispersion.

II. FLAT BEAMS IN THE LINAC

The acceleration of both bunches (e^- and e^+) in the linac from 1.19 to 47 GeV requires precision measurements, tight component tolerances and operational controls to maintain the 10 to 1 emittance ratio of the compressed damping ring beams.

Emittance measurements are made at three locations along the linac (at 1.2, 15, and 47 GeV) using three sets of four wires scanners. The resolution for the normalized emittance is $0.05\text{-}0.1\times10^{-5}$ m-rad. Typical vertical rms beam sizes at 47 GeV are 35 to 60 μm.

The required alignment tolerances are tight: the quadrupole rolls are corrected to 0.1 mrad, the quadrupoles and the beam position monitors are aligned to better than 100 μm, and the accelerating structures are aligned to about 300 microns (all rms). The linac support girders are mechanically clamped to reduce component vibration [5] to below 100 nm.

Transverse wakefield damping (BNS) is used in the first two-thirds of the linac to control emittance growth from beam trajectory jitter. Klystron phasing with an accuracy of 0.5

---

* Work supported by Department of Energy contract DE-AC03-76SF00515

Presented at the Particle Accelerator Conference (PAC 93), Washington, D.C., May 17-20, 1993.

degrees produces a small energy spread (0.3 % rms) at 47 GeV. Along the linac, eight transverse feedback groups (x,x',y,y' for two bunches) maintain the trajectory to about 50 μm with an update rate of 30 HZ.

Finally, the emittance growth from residual dispersion and wakefield effects is reduced by cancellation using "trajectory bumps" along the linac[6]. The transverse feedbacks are used to generate and close these bumps. They are tuned to control emittance and beam tails throughout the linac. About 8 to 12 bumps are in use at any given time with amplitudes of order 100-200 μm and lengths of 200 to 800 m. Most of these bumps are reasonably stable over several weeks, however, fine tuning (10%) is often done to track hourly and diurnal changes. For vertical emittances of the order of 0.5×10^{-5} m-rad, bump control at the 25 μm level is needed.

Emittance and Twiss parameters in key parts of the accelerator are measured automatically by the SLC control system every 30 minutes and recorded in long term history buffers for analysis as seen in Figure 1.

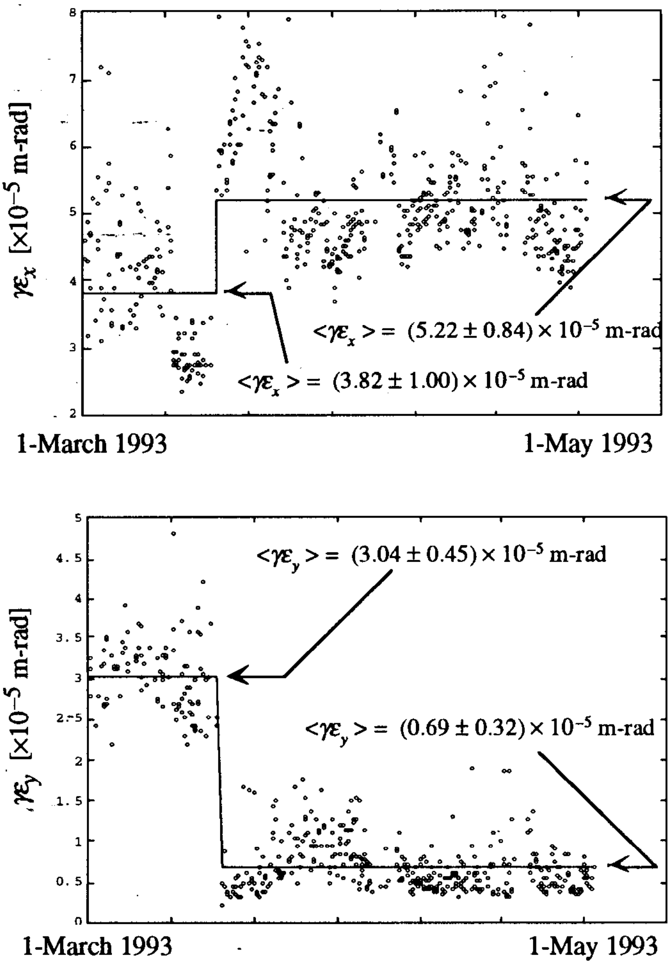

Figure 1. Horizontal (upper) and vertical (lower) invariant emittances for positrons as a function of time (March 1st to May 1st, 1993) at 47 GeV. The beams were made flat for collisions on March 17. The variations with time come from changing accelerator conditions and emittance optimization by the accelerator operators.

We observe from this data that a vertical invariant emittance in the range of $0.5\text{-}0.8\times10^{-5}$ m-rad can be maintained over long times during collisions at 3×10^{10} particles per bunch with 25 to 100% enlargement along the linac. The horizontal emittance can be maintained at $4.0\text{-}6.0\times10^{-5}$ m-rad with 20 to 50% increase along the linac.

During tests in 1992, vertical emittances of about 0.15×10^{-5} m-rad have been produced at 47 GeV at low beam intensity (1×10^{10}) and long store time in the damping ring [2].

III. FLAT BEAMS IN THE COLLIDER ARCS

The SLC Collider Arcs were designed with rolled achromatic sections to follow existing terrain elevations of the SLAC site [1]. In the presence of optical errors, the rolls generate coupling and vertical emittance growth due to synchrotron radiation. A well tested and refined optical correction algorithm [3] has been developed which measures and cancels both the net coupling and the local coupling in the arcs to within design tolerances. This is aided by an early hardware modification, known as 'rollfix', which distributes the roll transitions over several magnets [7] to improve the coupling cancellation in the presence of phase errors and also reduce the vertical emittance growth due to synchrotron radiation. Table 1 below summarizes the expected normalized emittance increase due to the synchrotron radiation of a perfect arc, with and without "rollfix", in both planes for each arc.

	$e-$ Arc		$e+$ Arc	
$\gamma\Delta\varepsilon$ [10^{-5} m-rad]	X	Y	X	Y
with out rollfix	1.22	0.25	1.19	0.27
with rollfix	1.30	0.07	1.13	0.12

Table 1. Synchrotron radiation emittance growth (10^{-5} m-rad) per plane of each arc before and after the implementation of "rollfix".

With this emittance growth and the full 4x4 measured arc transfer matrix, the flat beam emittance dilution in the arcs was estimated to be ≤20%. For incoming vertical linac emittances of $\sim0.5\times10^{-5}$ m-rad, the importance of the "rollfix" improvement is clear. In practice, the actual transport of flat beams through the arcs required little or no additional coupling correction beyond that already applied for round beams. The beam emittances at the end of the arcs were measured [12] and found consistent with the emittance growth cited above.

A new important achievement for flat beam running was the use of the north collider arc as a spin rotator by taking advantage of the strong resonance between the spin tune and the vertical betatron tune. A novel method was developed to perform arbitrary spin vector rotations with closed vertical betatron oscillations [4]. This method was very successfully tested and implemented early in 1993 so that the RTL and linac solenoid spin rotator magnets remained turned off for the entire 1993 luminosity run. If these solenoids were still used for the spin handling, a significant amount of new hardware (8 skew quads) and new tuning techniques would have been necessary to compensate for the beam rotations and preserve beam emittance.

IV. FLAT BEAMS IN THE FINAL FOCUS

Several new problems arise when considering the measurement and tuning of flat beams in the SLC Final Focus Systems. Beam-beam deflections [9] used to measure IP beam sizes and luminosity have, in the past, been fitted with a simplified round beam deflection curve. Fitting this curve to data from flat beam deflections (for present SLC parameters) produces a systematic underestimation of the luminosity of up to 25%. A correct flat beam deflection fit was developed to more accurately measure beam sizes and luminosity. Fig. 2 shows a vertical deflection scan and the fitted quadratic sum of the e^- and e^+ vertical beam sizes.

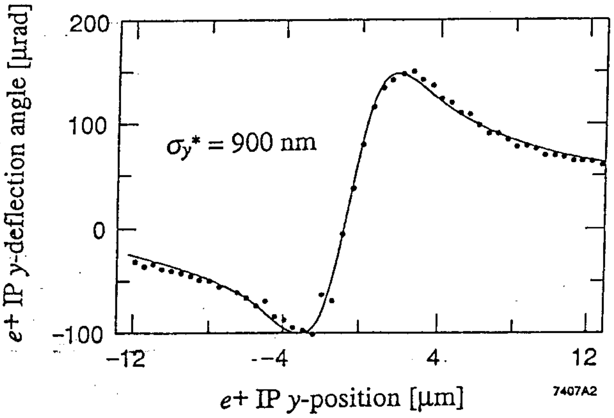

Fig 2. Flat beam-beam vertical deflection scan which measures the quadratic sum of the e^- and e^+ vertical beam sizes. The individual vertical beam sizes are <0.9 μm. The horizontal beam sizes (not shown) are typically 2.2-2.5 μm.

To correct residual coupling at the IP, each Final Focus employs just two skew quadrupoles. This is sufficient for equal emittances, but for a general solution four skew quadrupoles are necessary. By comparing a model of the linear optics of the combined arcs and final focus systems with the *measured* 4x4 arc transfer matrices, the existing Final Focus coupling correction was found to be adequate given the small residual arc coupling.

Third order optical calculations were required to determine the optimal IP beam divergences (β^*) for each plane. For round beams and 0.3% rms uniform energy spread the minimum beam size is achieved with a divergence of ~300 μrad rms in both X and Y. For present SLC flat beams ($\varepsilon_x/\varepsilon_y$ @IP = 6.0/0.6 $\times 10^{-5}$ m-rad), the optimal divergences are 350 μrad in X and 110 μrad in Y. This optics was established for flat beam collisions.

Beam-beam disruption is estimated to contribute about 10% [10] to luminosity with present SLC beam parameters (3×10^{10} particles per bunch, $\sigma_z \sim 0.75$ mm). An upgrade of the final focus optics is scheduled for completion before the 1994 SLC/SLD physics run. The new optics will substantially reduce the limiting third order aberrations and allow a smaller β_y^* (~1mm) at an optimal vertical IP beam divergence of 245 μrad. With these parameters, a vertical beam size of 350 nm is expected [11]. This will increase luminosity by a factor of 2.4 from geometry alone, with an additional 40% expected from the beam-beam pinch enhancement [10] (3.5×10^{10} particles per bunch, $\sigma_z = 0.6$ mm) giving a total improvement factor of 3.5.

V. CONCLUSIONS

Operating the SLC with flat beams has been very successful. The average luminosity doubled from 1.7×10^{29} cm^{-2}-sec^{-1} (18 Z_0/hr) with round beams to 3.0×10^{29} cm^{-2}-sec^{-1} (32 Z_0/hr) with flat beams. Operational problems were modest and the improvement was achieved within a few days. Peak luminosities beyond 40 Z's/h have been observed. At present, the integrated luminosity has reached a total of ~20,000 Z_0's, nearly doubling the entire 1992 round beam run with 11,000.

Spin manipulation in the arcs has been successful and stable; the electron polarization at the IP is currently averaging >60%.

VI. ACKNOWLEDGMENTS

The authors would like to thank the SLC operations and maintenance staff for their hard work and support.

VII. REFERENCES

[1] *SLC Design Book*, SLAC (December 1984).

[2] C. Adolphsen, F.-J. Decker, and J. Seeman, *Flat Beam Studies in the SLC Linac*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.

[3] T. Barklow, *et al.*, *Review of Lattice Measurement Techniques at the SLC*, Proceedings of the Advanced Beam Dynamics Workshop, Corpus Christi TX 1991, AIP Particles and Field Series 48.

[4] P. Emma, T. Limberg and R. Rossmanith, *The North Arc of the SLC as a Spin Rotator*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.

[5] J. Seeman, R. Holtzapple, and M. Ross, *Induced Beams Oscillations from Quadrupole Vibrations of about 2 Microns in the SLC*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.

[6] J. Seeman, F.-J. Decker, and I. Hsu, *The Introduction of Trajectory Oscillations to Reduce Emittance Growth in the SLC Linac*, XV Int. Conf. on HE Accel., Hamburg, Germany, 1992, p. 879.

[7] P. Bambade, *et al.*, *Rollfix — An Adiabatic Roll Transition for the SLC Arcs*, Proc. Particle Accelerator Conference, *Chicago*, Illinois (March 1989).

[9] P. Bambade, *et.al.*, "Observation of Beam-Beam Deflections at the Interaction Point of the SLAC Linear Collider", *Physical Review Letters*, Vol 62, No 25, p 2949, June 1989.

[10] P.Chen, *Disruption Effects from the Collision of Quasi-Flat Beams*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.

[11] N. Walker, *et al.*, *Third-Order Corrections to the SLC Final Focus*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.

[12] P. Raimondi, *et al.*, *Sigma Matrix Reconstruction in the SLC Final Focus*, Proceedings of 1993 Part. Accel. Conf., Washington, D.C., 1993.