The Stanford Linear Collider*

Paul Emma
Stanford Linear Accelerator Center
Stanford, California 94309

ABSTRACT

The Stanford Linear Collider (SLC) is the first and only high-energy e^+e^- linear collider in the world. Its most remarkable features are high intensity, submicron sized, polarized (e^-) beams at a single interaction point. The main challenges posed by these unique characteristics include machine-wide emittance preservation, consistent high intensity operation, polarized electron production and transport, and the achievement of a high degree of beam stability on all time scales. In addition to serving as an important machine for the study of Z^0 boson production and decay using polarized beams, the SLC is also an indispensable source of hands-on experience for future linear colliders. Each new year of operation has been highlighted with a marked improvement in performance. The most significant improvements for the 1994-95 run include new low impedance vacuum chambers for the damping rings, an upgrade to the optics and diagnostics of the final focus systems, and a higher degree of polarization from the electron source. As a result, the average luminosity has nearly doubled over the previous year with peaks approaching 10^{30} cm^{-2}s^{-1} and an 80% electron polarization at the interaction point. These developments as well as the remaining identifiable performance limitations will be discussed.

I. 1994-95 RUN SUMMARY

In 1994-95 the interaction point (IP) beam intensity has been raised to 3.5×10^{10} particles per bunch (ppb)—an increase made possible through the design and installation of new low impedance damping ring vacuum chambers [1]. The electron polarization has increased to 80% at the IP by using a 100 nm thin strained lattice GaAs photocathode in the electron source [2]. A major upgrade to the final focus optics allows a reduction of the IP vertical beta function which can produce an IP rms vertical spot size of 400-600 nm [3]. Work has continued throughout the run to improve beam stability via feedback refinements, optical modifications and magnet support alterations. The resultant number of Z^0 bosons logged by the SLD has increased from 11,000 at 23% e^- polarization in 1992, and 52,000 at 63% in 1993, to over 100,000 at 80% in 1994-95. Fig. 1 shows Z^0 production over this period. Due to scheduled interruptions and an increased number of various failures, machine up-time has been somewhat lower in 1994-95 (~65%) than in 1993 (~75%). Table 1 lists typical operating parameters at the IP along with an estimate of their variability over the extent of the run. The electron vertical emittance and positron intensity have been the most problematic in terms of variability. Detector backgrounds, which are generally quite low, also vary over the run. They are typically traced to the production of beam tails generated in the main linac.

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

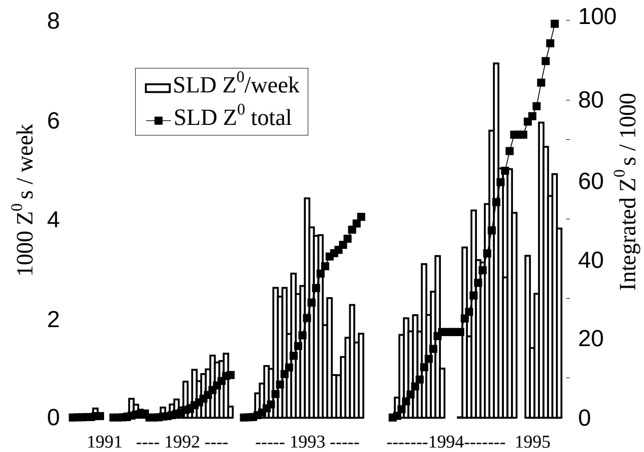

Fig 1. Z^0's per week and integrated Z^0's from 1991 to 1995.

Table 1. Typical IP operating parameters for the 1994-95 run.

beam energy	E	GeV	45.64
e^- intensity	N^-	10^{10} ppb	3.3-3.6
e^+ intensity	N^+	10^{10} ppb	2.9-3.7
hor. rms emittance	$\gamma\varepsilon_x$	mm-mrad	60-90
ver. rms emittance	$\gamma\varepsilon_y$	mm-mrad	10-25
rms energy spread	σ_δ	%	0.09-0.16
hor. rms beam size	σ_x	µm	2.0-2.6
ver. rms beam size	σ_y	µm	0.6-1.2
rms bunch length	σ_z	mm	0.7-1.1
Luminosity	L	10^{30} cm^{-2}s^{-1}	0.4-0.8
Z^0 bosons per hour	—	hr^{-1}	40-80
Repetition rate	f	Hz	120
e^- polarization	P_z	%	78-82
up-time	—	%	55-75

II. POLARIZED ELECTRON SOURCE

Since early 1992 the SLC has been operated exclusively with a polarized electron beam. The electron polarization at the source is now >80%—a significant increase over the 1992 and 1993 values of 25% and 65% respectively. The polarized electron source [2] presently uses a strained lattice GaAs photocathode which is biased at 120 kV and excited with circularly polarized light generated by a pulsed Ti:sapphire laser system. The source intensity is 7-8×10^{10} e^- per bunch (3.5×10^{10} at the IP). During the second half of the run, the cathode quantum efficiency was held below its maximum value in order to yield the highest possible polarization. Periodic cathode recesiations are performed every ~5 days through a simple computer automated process which requires ~20 minutes to complete. The system has been remarkably reliable with <2% unscheduled downtime. The success of the high energy colliding beam physics program at the SLC is due in large part to the success of the polarized electron source.

III. DAMPING RINGS AND BUNCH COMPRESSORS

One of two major SLC upgrades for 1994 was the design and construction of new low impedance vacuum chambers for the damping ring arc-sections [1]. Measurements made in 1992 showed the onset of a bunch length 'sawtooth' instability at beam currents of ~3×10^{10} ppb [4]. This high current instability also appeared as variations (jitter) in the extracted beam phase which produced errant flyer pulses and associated linac collimator losses and detector backgrounds. The net result was to limit the pre-upgrade SLC beam currents to <3×10^{10} ppb. The cause of this instability was the high impedance damping ring vacuum chamber which, prior to 1994, had a computed inductance of 37.5 nH [5]. An interim solution used in 1993 was to ramp the rf voltage down just after injection thereby lengthening the bunch and holding the peak current below the instability threshold [6]. The voltage was ramped up again just before extraction. This procedure necessitated the use of direct rf feedback to compensate increased beam loading at reduced voltage.

The new vacuum chamber has many fewer flexible bellows. Electro-discharge machining (EDM) methods were used to produce smoother transition pieces. The resultant impedance is seven times smaller than that of the old chamber [7]. Measurements show a significantly shorter bunch length and a reduced high intensity lengthening. Fig. 2 shows the measured bunch length at extraction versus beam intensity both for the old and the new vacuum chambers. A single bunch instability is still observed, but it is less severe and no longer limits the SLC operating intensity [1].

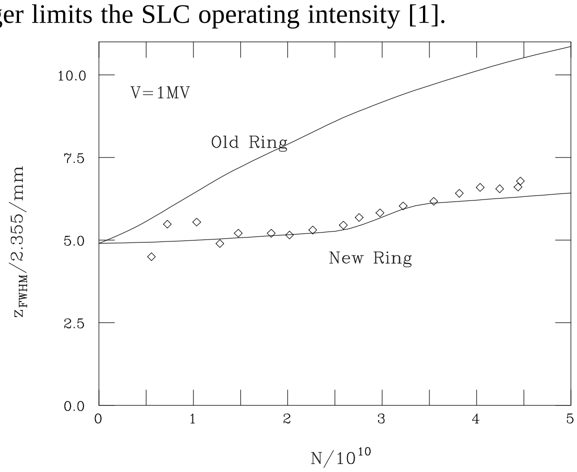

Fig 2. Damping ring extracted bunch length vs. e^- intensity for *old* and the *new* vacuum chamber. Data points represent measurements performed on the new chamber in 1994.

At the nominal machine repetition frequency of 120 Hz the electron store time (~8 msec) is half that of the positron ring (~16 msec). Consequently, the electron damping time is more critical. In 1993 a reduction in transverse partition numbers was achieved by stretching the ring circumference in order to shorten the transverse damping time by ~15% [8]. Recent measurements show damping times of 3.3-3.6 msec horizontally and 4.1-4.2 msec vertically [9]. With an 8.3 msec store the typical extracted electron vertical emittance is 2-3 mm-mrad while it is possible to achieve <1 mm-mrad with a 16 msec store at a repetition rate of 60 Hz.

In the past, effort has been devoted to correcting transverse emittance dilution in the SLC bunch compressors [10-11]. Skew quadrupoles, skew sextupoles and octupole magnets were installed in previous years to correct first, second and even third order anomalous dispersion. The large energy spread (~1%) and the strong bending necessary for a potential ten-fold bunch length compression present severe alignment, construction and multipole field error tolerances. These efforts have been, for the most part, successful. However a 10-30% emittance dilution remains (partially due to an increased compressor voltage—see below). Efforts need to continue here.

The form of bunch compression was changed in 1994. Prior to this, the bunch was 'under-compressed' to 1.3 mm with a 29 MV rf voltage which initiates a <90˚ longitudinal phase rotation. Starting in 1994 the bunch is now 'over-compressed', also to 1.3 mm, but by using an rf voltage of 41 MV for a phase rotation of >90˚. The motivation is to reduce the end-of-linac energy spread by partial cancellation of energy spread due to the longitudinal wakefield in the linac and that due to rf curvature [12]. This technique successfully reduced the end-of-linac energy spread from ~0.25% prior to 1994, to ~0.12% rms. In addition, long low-energy tails in the bunch distribution are no longer generated. A small compromise is made in beam transmission through the compressor beamline where large dispersion and increased energy spread (~1% at 29 MV and ~1.4% at 41 MV) produce a 5-10% beam loss.

IV. MAIN LINAC

The main linac challenge is in high current emittance preservation and stabilization of both the e^- and e^+ bunches in the presence of the inevitable quadrupole and accelerating structure misalignments. The requirements for vertical linac emittance control have become even more challenging with the advent of flat beam operation in 1993 where the linac entrance emittance at 1.2 GeV is now: $\gamma\varepsilon_y \approx$ 2-3 mm-mrad, $\gamma\varepsilon_x \approx$ 30-40 mm-mrad [13]. Beam-based alignment techniques have been used successfully in the past to control transverse quadrupole alignment to ~80 µm rms [14] and new ideas are under investigation to align the disk-loaded wave guides using beam generated dipole wakefields of the accelerating structures as an error signal [15]. Under normal operation, empirical linac emittance correction is accomplished by introducing feedback controlled trajectory oscillations [16] to minimize the measured emittance of wire-scanner phase space monitors [17] or by observing a set of four off-axis screens [18]. Emittance dilution in the main linac is usually controllable to <60% vertically and <30% horizontally at 3.5×10^{10} ppb. However, temperature dependencies in the linac rf system can generate day to night emittance variations which require constant tuning. Improvements are presently under investigation [19].

A second challenge is pulse-to-pulse and long term trajectory stabilization of both the e^- and e^+ beams [20]. Trajectory jitter not only degrades luminosity but also complicates and slows tuning schemes which rely on phase space monitors requiring many tens or hundreds of pulses. A large source of e^- trajectory jitter, identified in 1994, was due to long range transverse wakefields. With equal e^+ and e^- linac betatron phase advance, the jitter in the leading e^+ bunch is resonantly amplified to the trailing e^- bunch. By introducing a vertical e^+ betatron oscillation initiated in the positron bunch compressor, the trailing electron bunch is seen to accumulate an oscillation due to the long range wakefield [21].

This problem was significantly diminished by introducing a 10˚/cell separation between the horizontal and vertical betatron tunes within the linac. Thus the resonant condition is avoided. This linac lattice modification successfully reduced e^- vertical trajectory jitter from ~60% of the nominal rms beam size (observed in the final focus) to ~40%. Some improvement is also observed in e^- horizontal jitter. Fig. 3 shows the initiated e^+ oscillation and its wake induced e^- oscillation both with and without a split tune lattice.

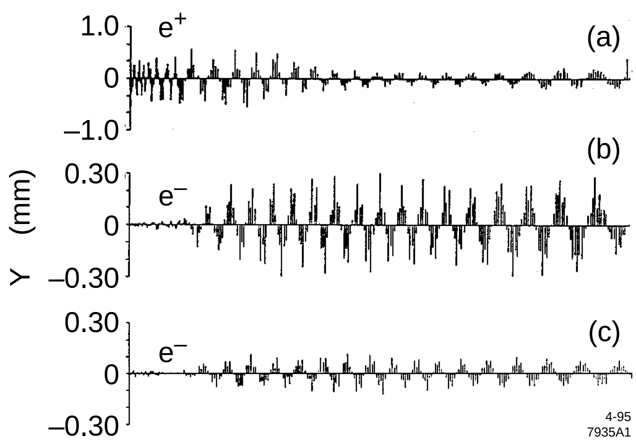

Fig 3. Vertical e^+ oscillation introduced before the linac (a) and long range wakefield induced oscillation for e^- beam of ~300 µm before (b) and ~100 µm after (c) installation of split tune lattice.

However, with the large mid-linac energy spread introduced for BNS damping [22] and the new 'split-tune' quadrupole settings, some increased chromatic emittance dilution within the linac is expected (~10%). Efforts are underway to develop a split-tune linac lattice with less chromatic dilution.

In light of previous successes [23], further efforts to stabilize linac trajectories have centered around modifications of quadrupole magnet support structures. Measurements of quadrupole magnet vibrations using a geophone indicate ~300 nm rms vibrations for frequencies above 1 Hz [24]. Beam response modeling in these conditions predict trajectory jitter which is ~20% of the 10-50 µm nominal vertical beam size. Inspection of the supports has revealed a poorly supported degree of freedom in magnet pitch angle which translates into a significant vertical displacement component due to the longitudinally biased pitch rotation axis of the support. In response, magnet pitch wedges were installed for ~2/3 of the linac quadrupoles.

V. ARCS AND FINAL FOCUS SYSTEMS

Prior to the 1994 run the optics of both final focus systems (FFS)—e^- & e^+—were upgraded in order to allow reduction of the IP vertical beta function [25]. One new quadrupole magnet per FFS was installed between the chromatic correction section (CCS) and the final triplet. This quadrupole optimally adjusts the betatron phase advance between CCS sextupoles and triplet to reduce the dominant 3rd order aberration (U_{3466} coefficient in TRANSPORT notation [26]). In addition, two more quadrupoles—one skew and one normal—were added to the upper transformer section (UT) to provide a full compliment of orthogonal tuning 'knobs' for control of IP beta functions, cross-plane coupling and IP beam waist positions [27]. Four new wire-scanners per FFS were added for emittance and matching diagnostics within the FFS and a fifth wire-scanner was installed at an IP image point in the center of the first CCS bend magnet [28].

The *new* final focus beamlines were commissioned in April and May of 1994 using previously established techniques such as quadrupole and sextupole beam-based alignment methods [29-31]. The new orthogonal UT tuning knobs and image point wire-scanners were employed very successfully to achieve the desired IP beta functions, coupling correction and waist positions. Subsequent low current beam collisions (0.5-1.0×10^{10} ppb) using a twice nominal e^- damping ring store time to achieve ideal emittances produced vertical IP rms spot sizes of 400 nm, clearly confirming the expected performance of the upgrade. The horizontal spot sizes observed were also within the expected value of 1.8-2.0 µm. Fig. 4 shows a 413 nm vertical beam-beam deflection scan [32] measured at low current and long damping ring store.

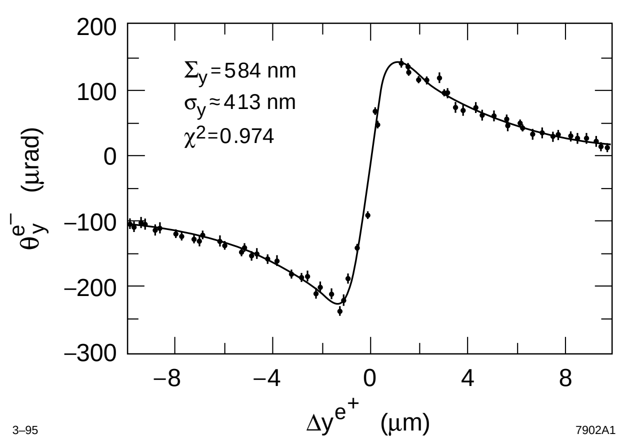

Fig 4. Beam-beam deflection, θ, vs. separation, Δy, fitted with Bassetti-Erskine formula showing 413 nm vertical rms beam size.

At higher beam intensities a significant emittance dilution within the arc/FF systems appears which is not yet understood. The dilution is usually most evident for the electrons in the vertical plane. At 3.5×10^{10} ppb the observed luminosity is typically 20-40% lower than expectations based on emittance measurements at the end of the main linac. Numerous machine studies have addressed this discrepancy [3]. One probable explanation for high current emittance dilution is collimator generated wakefields. The collimators are used to attenuate detector backgrounds by clipping thinly populated beam tails and are downstream of the end-of-linac wire-scanners used for emittance measurements. Recent studies [33] show clear emittance dilution for some collimators which are routinely closed to within ~3-5 times the rms beam size. However, these measurements have not been reproducible and they are sensitive to varying orbits and beam conditions in the collimator regions.

The addition of new wire-scanners at the entrance to the FFS allowed a first direct observation of the emittance at the end of the 1.2 km, terrain-following collider arcs. At the start of the run the emittance increase through the arcs was found to be independent of both beam current and initial emittance. The vertical increase was $\Delta\gamma\varepsilon_y \approx$ 3-4 mm-mrad while the horizontal was $\Delta\gamma\varepsilon_x \approx$ 10-12 mm-mrad, both of which are in fair agreement with the expected effect of synchrotron radiation and cross-plane coupling calculated from measured betatron oscillation data [34]. Without imperfections the vertical emittance increase in the arcs is expected to be ~1 mm-mrad. However, toward the end of the run, the arc emittance increase showed some sensitivity to beam current, especially for electrons in the vertical plane. It is not yet known if this apparent change was due to a slow degradation of the orbits and optics of the arcs or if it was related to collimator generated wakefields. Careful experiments designed to study current dependencies in the arcs were attempted but are difficult to perform satisfactorily due to problems controlling main linac emittances at varying currents.

Spin transport through the SLC continues to be controlled with vertical orbit 'bumps' in the e^- (north) collider arc [35]. The two post-damping ring spin rotator solenoids have remained switched off. Depolarization in the arcs due to initial energy spread has been reduced in comparison to the previous year by a vertical arc orbit variation method which empirically reduces the effective number of spin precessions through the arc from ~17 'turns' (full precessions) in 1993 to ~10 turns in 1994 [36]. This improvement, in conjunction with the reduction in energy spread using over-compression, has reduced the arc depolarization from ~3% in 1993 to <1% in 1994-95.

VI. FEEDBACK, CONTROLS AND DIAGNOSTICS

There are approximately 28 different microprocessor controlled fast trajectory feedback loops, as well as several special function loops, in simultaneous operation around the SLC [37]. These loops maintain beam trajectories and energies over a broad band of frequencies up to ~10 Hz. Beam position monitors are used to measure trajectory variations around a previously determined reference orbit and corrections are applied with fast dipole correction magnets or multiple klystron phases in the case of energy corrections. There are seven loops in the main linac which control both e^- and e^+ orbits. These loops are 'cascaded' through a communication link so that loop n+1 nominally corrects only trajectory disturbances incurred after loop n. Furthermore, the loops are 'adaptive' meaning they are able to learn the transport map—the accelerator transfer coefficients—between loops. An added benefit of adaptive-cascaded feedback is the continual measurement of the phase advance between points in the accelerator. This information is recorded every six minutes and can be used to trace and isolate optical errors such as errantly back-phased klystrons. Efforts continue to improve feedback performance through step response testing and modeling [38].

The beginnings of significant progress in machine wide emittance control can be traced to the development and installation of beam profile wire-scanners in the main linac in 1990-91 [17]. Transverse emittance measurements for both beams are now automatically made at three different points in the main linac during colliding beam operations once every hour. In addition, operator initiated measurements are used to direct tuning efforts when necessary. There are now ~50 different wire-scanners in use throughout the SLC from the 40 MeV electron injector to near the final triplet. Most of these wire-scanners are able to measure beam sizes in both planes as well as the x-y correlation. Extensive software controls have been developed which analyze the beam profile data collected and return parameters such as emittance, beta-functions, magnitude and phase of mismatch, coupling magnitudes and beam tails. These parameters, along with raw beam size, are available in history plots for any time interval during the run.

VII. PRESENT PERFORMANCE LIMITATIONS AND FUTURE PLANS

Table 2 below summarizes 1995 peak operating parameters with respect to the original 1985 'design' expectations. The design expectations are unrealistic, especially in their underestimation of linac wakefield emittance dilution at beam intensities of $>7\times10^{10}$ ppb.

Table 2. Design and peak 1995 parameters most disparate. The intensity difference accounts for a factor of ~8 in luminosity.

PARAMETER	UNITS	DESIGN	1995
Intensity	1×10^{10} ppb	7.2	3.5
repetition rate	Hz	180	120
hor. emittance	mm-mrad	30	60
ver. emittance	mm-mrad	30	10
hor. IP beam size	μm	1.65	2.1
ver. IP beam size	μm	1.65	0.7
energy spread	%	0.25	0.12
Enhancement	—	2.2	~1.15
Luminosity	10^{30} cm^{-2}s^{-1}	6.0	0.8
Z^0 per hour	hr^{-1}	650	80
e^- polarization	%	—	80

The difference between ‘design’ and 1995 intensities alone, including associated loss in enhancement, accounts for a factor of ~8 in luminosity. Another factor of 1.5 is evident in the repetition rate—not attainable due to modulator limitations. With these past limitations acknowledged, the progress of the SLC is actually quite remarkable. The achieved IP vertical beam sizes have in fact far outperformed the design expectations. This is a result of flat beam operation, not foreseen in 1985, and the 1994 final focus optics upgrade.

The present peak performance parameters are, however, not always maintainable. There are still unexplained variations in the luminosity over all time scales. Some of these variations are traceable to end-of-linac emittances and are partially attributed to temperature variations. However, some variations remain unexplained and are possibly due to an undiagnosed high current dilution mechanism within the collimation, arc or final focus systems. A 20-40% discrepancy still exists between the expected and observed luminosity. This appears to be current dependent and will be the main focus of attention in subsequent collider runs. Efforts are under way to understand and correct the large vertical synchrotron radiation induced emittance growth within the collider arcs.

Future SLC plans include the installation of an IP ‘laser-wire’ in 1996 which allows single beam size measurements down to ~300 nm [39]. Many smaller projects are in progress which address reliability issues and beam transmission limitations in the various transport lines. The goals for the collider are to record 500,000 Z^0’s over the next three years.

VIII. ACKNOWLEDGMENTS

The continuing progress in the performance of the SLC is in a large part due to the persistence of the operations staff who have learned and developed many new ways to deal with the full spectrum of problems encountered in daily operations. Their efforts are fully acknowledged here. Further acknowledgments are extended to the SLC physicists, the engineering groups and the maintenance staff.

IX. REFERENCES

[1] K. Bane et al., *High Intensity Single Bunch Instability Behavior in the New SLC Damping Ring Vacuum Chamber*, these proceedings (1995).
[2] R. Alley et al., *The Stanford Linear Accelerator Polarized Electron Source*, SLAC-PUB-6489, April 1994.
[3] F. Zimmermann et al., *Performance of the 1994/95 SLC Final Focus System*, these proceedings (1995).
[4] P. Krejcik et al., *High Intensity Bunch Length Instabilities in the SLC Damping Rings*, PAC 1993, Washington (1993).
[5] K. Bane, *Bunch Lengthening in the SLC Damping Rings*, SLAC-PUB-5177 (1989).
[6] P. Krejcik et al., *RF Feedback for Beam Loading Compensation in the SLC Damping Rings*, PAC 1993, Washington (1993).
[7] K.L.F. Bane, C.K. Ng, *Impedance Calculations for the Improved SLC Damping Rings*, PAC 1993, Washington.
[8] M.G. Minty et al., *Using a Fast Gated Camera for Measurements of Transverse Beam Distributions and Damping Times*, Accel. Instr. Workshop, Berkeley (1992).
[9] C. Simopoulos, R.L. Holtzapple, *Damping Rate Measurements in the SLC Damping Rings*, these proceedings (1995).
[10] C. Adolphsen et al., *Chromatic Correction in the SLC Bunch Length Compressors*, PAC 1991, San Francisco, CA (1991).
[11] P. Emma, W. Spence, *Grid-Scans: A Transfer Map Diagnostic*, PAC 1991, San Francisco, CA (1991).
[12] F. J. Decker et al., *Over-Compression: A Method to Shape the Longitudinal Bunch Distribution for a Reduced Energy Spread*, Proc. of the 1994 International Linac Conference, Tsukuba, Japan (1994).
[13] C. Adolphsen et al., *Flat Beams in the SLC*, PAC 1993, Washington (1993).
[14] C. Adolphsen et al., *Beam-Based Alignment Technique for the SLC Linac*, PAC 1989, Chicago (1989).
[15] P. Krejcik et al., *Direct Measurement of Transverse Wakefields in the SLC Linac*, these proceedings (1995).
[16] J. T. Seeman et al., *Introduction of Trajectory Oscillations to Reduce Emittance Growth in the SLC Linac*, HEACC’93, Hamburg, (July 1993), p. 879.
[17] M.C. Ross et al., *Wire Scanners for Beam Size and Emittance Measurement at the SLC*, PAC 1991, San Francisco (1991).
[18] F.-J. Decker et al., *Beam Size Measurements with Non-interceptive Off-Axis Screens*, PAC 1993, Washington.
[19] F.-J. Decker et al., *Effects of Temperature Variation on the SLC Linac RF System*, these proceedings (1995).
[20] P. Krejcik et al., *Pulse to Pulse Stability Issues in the SLC*, these proceedings (1995).
[21] F.-J. Decker et al., private communication (1995).
[22] V. Balakin, A. Novokhatsky, V. Smirnov, 12th International Conference on High Energy Accelerators, FNAL, 1983, p. 119.
[23] J.T. Seeman et al., *Induced Beam Oscillations from Quadrupole Vibrations of About 2 Microns at SLC*, PAC 1993, Washington (1993).
[24] J.L. Turner et al., *Vibration Studies of the Stanford Linear Accelerator*, these proceedings (1995).
[25] N. Walker et al., *Third Order Correction to the SLC Final Focus*, PAC 1993, Washington (1993).
[26] K. L. Brown et al., *TRANSPORT*, SLAC-91, (1977).
[27] N. Walker et al., *Global Tuning Knobs for the SLC Final Focus*, PAC 1993, Washington (1993).
[28] D. McCormick et al., *Measuring Micron Sized Beams in the SLC Final Focus*, Sixth BIW, Vancouver (1994).
[29] P. Emma, *Beam Based Alignment of Sector-1 of the SLC Linac*, 3rd EPAC, Berlin (1992).
[30] P. Emma et al., *Beam Based Alignment the SLC Final Focus Sextupoles*, PAC 1993, Washington (1993).
[31] P. Raimondi et al., *Beam Based Alignment the SLC Final Focus Superconducting Final Triplets*, PAC 1993, Washington (1993).
[32] P. Raimondi, F.-J. Decker, *Beam Size Measurement with Flat Beams in the SLC Final Focus*, these proceedings (1995).
[33] K.L.F. Bane et al., *Measurements of the Effects of Collimator Generated Wakefields on the Beams in the SLC*, these proceedings (1995).
[34] T. Barklow et al., *Review of Lattice Measurement Techniques at the SLC*, Proceedings of the Advanced Beam Dynamics Workshop, Corpus Christi, TX (1991).
[35] T. Limberg et al., *The North Arc of the SLC as a Spin Rotator*, PAC 1993, Washington (1993).
[36] P. Emma et al., *Depolarization in the SLC Collider Arcs*, 4th EPAC, London (1994).
[37] T. Himel et al., *Adaptive Cascaded Beam-Based Feedback at the SLC*, PAC 1993, Washington (1993).
[38] M.G. Minty et al., *Optimization of Feedback Performance at the Stanford Linear Collider*, these proceedings (1995).
[39] M.C. Ross et al., private communication (1995).