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STATUS OF THE SLC*

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ABSTRACT

The construction project for the SLAC Linear Collider (SLC) was officially completed in April 1987, following a successful test in March of passing 46-GeV positron and electron beams through the collider hall on the same accelerator pulse. Since that time, commissioning of the SLC has concentrated on making the stability, intensity and transverse dimensions of both beams suitable to generate useful luminosity near the center of mass energy of 93 GeV.

1. INTRODUCTION

The SLC is the first linear collider and was designed to provide high luminosity electron-positron collisions for studying the production of the Z^o. A schematic layout of the SLC is shown in Fig. 1. The basic design parameters are shown in Table 1. The design luminosity is ambitious and will require several years to achieve. It is fortunate that interesting physics of the Z^o can be obtained with a luminosity of $6 \times 10^{27} cm^{-2} sec^{-1}$ which is our initial goal for Fall 1987. The presently achieved conditions are also shown in Table 1. Steady progress is being made, and the expectations that we will meet our initial goal are high. The state of each subsystem of the SLC is reviewed here concentrating on areas of present study.

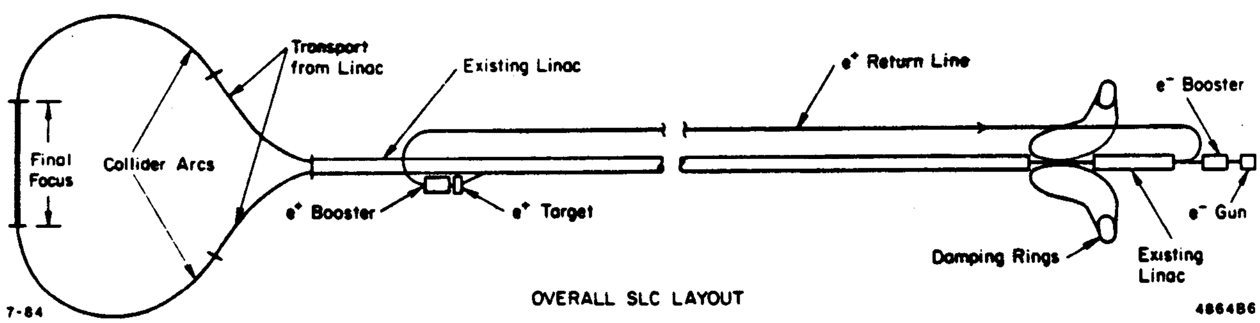

Fig. 1. Schematic layout of the SLC.

2. COMMISSIONING OF THE SLC

Beam testing of components and SLC subsystems has been an ongoing enterprise since the fall of 1980 when the initial studies of the control system and injector began. In May 1986, commissioning of the full SLC began with the goal of tying the various subsystems together. By August 1986, damped electron beams were being extracted from the north damping ring for routine operation in the downstream portions of the machine. Two electron bunches on a single RF pulse were injected and stored in the north damping ring during October 1986. Positron bunches were first accelerated to the damping ring energy of 1.21 GeV in the following month, November. During December, electrons were first accelerated to an energy of 50 GeV at the end of the linac. Electrons were subsequently transported to the final focus

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Table 1.

Basic parameters for the SLC.

	Design Goal	Initial Goal	Achieved	Units
Beam energy at IP	50	46	46	GeV
Beam energy at end of linac	51	47	53	GeV
Electrons at entrance of arcs	7×10^{10}	10^{10}	3.5×10^{10}	
Positrons at Entrance of arcs	7×10^{10}	10^{10}	0.6×10^{10}	
Repetition rate	180	60	5	Hz
Bunch length (σ_z in linac	1.5	1.5	$0.5 - 3^a$	mm
Normalized transverse emittance at end of linac (electrons)	3×10^{-5}	10×10^{-5}	$3 - 20 \times 10^{-5}$	rad-m
Spot radius at IP	1.6	2.8	—	μ
Luminosity	6×10^{30}	6×10^{27}	—	$cm^{-2}\ sec^{-1}$

[a]Bunch length increases with current:
at 1.2×10^{10}/bunch, the bunch length is 1.5 mm in the linac.

region through the north arc during February 1987. Electrons were transmitted across the interaction point (IP) in March 1987. Also in March, damped positrons were extracted from the south damping ring; positrons and electrons were coaccelerated through the linac on the same RF pulse; and positrons were transmitted through the south arc. On March 27, 1987, electrons and positrons crossed at the IP signifying the completion of the construction phase of the SLC project.

Since the initial crossing at the IP, commissioning has continued. The present goal of the current commissioning effort is to tune the system so that useful luminosity can be achieved by the fall of 1987. The initial luminosity goal has been set to be $6 \times 10^{27}\ cm^{-2}s^{-1}$. This goal is met by colliding 10^{10} electrons on 10^{10} positrons at 120 pps with an IP spot radius of 4 microns.

3. INJECTOR

The SLC injector[1] consists of an electron source and 100 meters of linac. The source is required to produce a pair of electron bunches which are accelerated through the initial portion of the linac for injection into the north damping ring. A single positron bunch is injected at 200 MeV and accelerated along with the electron bunches to the damping ring energy. Positrons are transported into the south damping ring. Control of the energies and energy spread of the three bunches are required for efficient injection into the damping rings. Intensity stabilization is important in the control of energy jitter of beams extracted from the damping rings. In addition, proper adjustment and stabilization of the temporal spacing of the bunches is necessary so that colliding beams always cross at the same location in the interaction hall.

As of June 1987, the electron source is fully operational. Pairs of electron bunches, spaced by 61.6 ns, can be accelerated and stabilized in energy for injection into the north damping ring.

At bunch currents greater than about 7.5×10^{10} intensity jitter becomes a problem. At present, the source is operated to produce electron bunch intensities between about 5×10^9 and 3×10^{10} particles per pulse according to the demands of the downstream users. Operation at 1×10^{10} electrons per pulse is not a problem.

Positron transmission through the injector region depends upon the initial positron launch conditions. An increased positron bunchlength enlarges the energy spread which results poor transmission and injection into the south ring. Best conditions achieved so far resulted in 60% transmission through the injector into the ring. Transmission efficiencies of 40% are typically achieved.

Whereas double electron bunch operation has been tested, only single bunches are routinely accelerated through the injector region. Two bunch operation is awaiting the installation of a two bunch extraction kicker in the north damping ring. Similarly, the low repetition rate of the SLC (10 pps in the linac) has not permitted testing of the full three bunch acceleration in the injector. Testing of three bunch operation is scheduled for the fall of 1987 and is not expected to be a problem.

4. POSITRON SOURCE

The SLC positron source[2] consists of a W-Re target, flux concentrator, 200 MeV of acceleration, and a 2000 km transport line. At the two-thirds point in the linac, 30 GeV electrons are deflected onto the target. Positrons in the resultant shower are accelerated to 200 MeV in a s-band, high gradient capture section followed by three standard SLAC sections. The 200 MeV positrons are transported to the beginning of the linac for subsequent acceleration to 1.21 GeV and injection into the south damping ring.

Initial plans called for a rotating, water cooled target. Testing of the device resulted in a vacuum failure of the rotating seal; the failure caused damage to the high gradient section. At present, a fixed target has been installed and the high gradient section is operated at 20 MeV per meter instead of the design goal of 50 MeV/meter. The fixed target is limited in power dissipation to the equivalent of 2×10^{10} incident electrons per pulse at a repetition rate of 120 pps. Solenoids installed around the capture section have developed turn to turn shorts resulting in a reduction of the fields in the capture region.

The failure of the high gradient section and reduced solenoidal field decreases the electron to positron efficiency. The restriction of the maximum intensity on target, further limits positron production. Plans call for replacement of the solenoids and high gradient section in the fall of 1987. This will result in greater positron yields. Development of a rotating target to absorb greater electron fluxes is not anticipated until sometime in 1988.

With the reduced conditions, a yield of one positron injected into the linac from the south damping ring for every two electrons incident on target has been achieved. The maximum number of positrons stored in the south ring has been approximately 1×10^{10} particles in a single pulse. In order to accomplish this yield, careful tuning of the positron bunchlength was required. This tuning was done by varying the RF phase in the capture section, tuning the subsequent downstream RF and transport line magnets, while observing the bunchlength using a streak camera. Fortuitously, the yield peaks where the bunchlength is minimized. The smallest achieved bunchlengths are approximately 1.5 times longer than can be expected to fit inside the damping ring energy aperture, after acceleration through the injector. This increase is attributed to a longer than expected bunchlength of electrons extracted from the north damping rings.

Reduction of the incident electron bunchlength, installation of a new high gradient section and capture region solenoids, as well as improved positron orbit control through the injector region are expected to bring the yield of damped positrons up to nearly one per electron incident on target by the fall of 1987. This improvement, will permit operation of 1×10^{10} positrons per pulse in the collider hall for the same number of electrons on target.

5. DAMPING RINGS

Two damping rings[3] have been built to reduce the transverse emittance of the positron and electron bunches to a value of $\gamma\epsilon = 3 \times 10^{-5}$ m-rad required for micron sized spots at the IP. Table 1 lists the design parameters of the SLC rings. Construction and development on the rings began in 1982. The north damping ring was completed in the spring of 1986. Routine operation of the electron ring (the north damping ring) for single bunch operation in conjunction with the SLC linac began in August 1986. A two bunch injection kicker[4] was installed in the north ring in the fall of 1986 and a pair of electron bunches of about 2.5×10^{10} particles each were stored in the north during October 1986. The rebuilt south damping ring was commissioned with electrons in the winter of 1986–1987. This ring was reversed in polarity to accept positrons; positrons were first injected into and extracted from the south ring in March 1987.

A two bunch extraction kicker is being prepared for installation in the north ring for the fall of 1987. Extraction kicker pulse jitter is expected to be within tolerance for operation at 1×10^{10} electrons per pulse but may not be acceptable for higher bunch currents.

Bunch lengthening has been observed in both damping rings. Figure 2 shows the equilibrium bunchlength in the north damping ring as a function of beam current. The design parameters predict an rms equilibrium bunchlength of 5.9 mm . As seen in Figure 2, the design size is achieved at the lowest currents and increases with current. A straight line fit to the data is shown in the figure. Figure 3 illustrates the equilibrium energy spread in the ring as a function of beam current. This figure indicates a threshold of turbulent bunchlengthening at a current of about 1.5×10^{10} particles per bunch. Similar results have been observed in the south damping ring. Model calculations using calculated impedances of bellows, BPMs, vacuum chamber transitions and irregularities predict the observed bunchlengthening with reasonable agreement.[5]

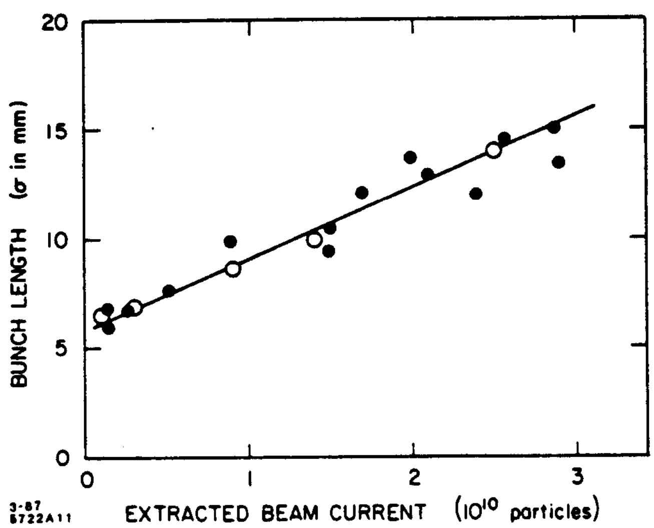

Fig. 2. Equilibrium bunchlength in the damping rings as a function of beam current.

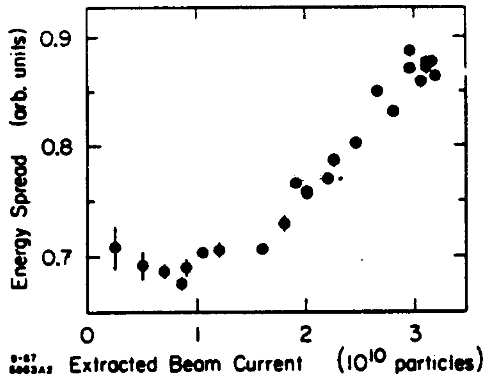

Fig. 3. Equilibrium energy spread in the damping rings as a function of beam current.

The bunch lengthening reduces the maximum usable beam current to about 2×10^{10} particles per pulse. Even though it is possible to extract higher currents from the ring, it is not possible to compress the large bunchlengths in the transport line leading from the rings to the linac (RTL) because of energy aperture restriction in the RTLs. Furthermore, the minimum achievable bunchlength is limited by the equilibrium energy spread which increases above the turbulence threshold. An increased longitudinal beam size results in increased sensitivity to transverse wakefields in the linac. In addition, the increased scavenger bunchlength results in increased positron bunchlengths which are subsequently difficult to inject into the south damping ring because of an enlarged energy spread.

Several short term solutions are being considered for the fall of 1987. These include shielding the ring bellows, enlarging the RTL energy aperture, and increasing the available RF voltage in the ring. Some precompression in the rings is possible by launching a longitudinal quadrupole oscillation in the ring shortly before extraction and extracting the beam when a minimum in the beam size occurs. These fixes and procedures are expected to increase the maximum useful beam current to nearly 5×10^{10} particles per bunch. For operation at 1×10^{10} particles per pulse, the present system is adequate.

6. LINAC

The two mile SLAC linac has been upgraded [6] to accelerate tightly focused beams of positrons and electrons on the same RF pulse without significant emittance increases. Over 200 new 67 MW klystrons have been installed in the linac, and beam energies of 53 GeV have been measured.[7] Routine commissioning operates at 47 GeV per beam. 3.5×10^{10} electrons and 0.6×10^{10} positrons per bunch have been accelerated without loss.

Beam trajectories are corrected using dipole magnets and beam position monitors located every 12 meters (closer in the first 300 meters). Electron trajectories are routinely corrected to errors of 125 μ rms. When both beams are corrected simultaneously, typical trajectory errors are 300 μ rms for each beam. These trajectory errors have been steadily decreasing as the misaligned quadrupoles and errant electronic modules have been discovered and fixed.

The transverse shapes of the beams at the end of the linac depend on the quadrupole lattice, the energy-acceleration profile of the linac, entrance conditions from the RTLs, and transverse wakefields. The beam dimensions have been shown to remain constant as long as the upstream conditions do not change. The transverse beam emittances have been measured at high energy as a function of beam current, and a summary is shown in Table 2. Above about 0.8×10^{10} electrons per pulse the bunch length increases due to the damping ring which increases the beam's energy spectrum dramatically in the linac. This causes sharply increased transverse wakefields and chromatic phase dilution effects to

Table 2.

Measured linac invarient emittances at 43–47 GeV. The units are in radian-meters $\times 10^{-6}$.

$I \times 10^{10}$	Horizontal	Vertical	Date
0.4	7 ± 1	2 ± 1	2/87
0.4	8 ± 1	3 ± 1	8/87
0.8	12 ± 4	1.1 ± 0.3	2/87
1.0	25 ± 5	2 ± 1	2/87
1.5	20 ± 5	4 ± 1	2/87

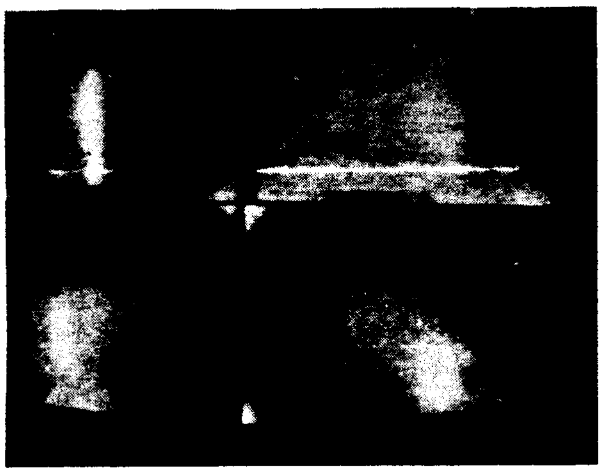

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Fig. 4. Digitized beam shape monitor at the end of the linac used for maintaining linac conditions. The left images are used to monitor the vertical phase space of the electrons, the right images the horizontal. This monitor uses less than one percent of the linac pulses at 120 Hz.

appear. Improvements to the damping rings should reduce this effect. Thus, the apparent emittance increase above 10^{10} particles will improve.

An online monitor of the beam shapes at the end of the linac has been built. Four off axis profile monitors and four low repetition rate pulsed dipoles sample the beam at one hertz. The resulting images of the beam shapes are digitized and stored. The images are used by the operators to verify that linac conditions have not changed. The screens were installed so that pairs of monitors were 90 degrees in betatron phase space apart allowing a good check of the phase ellipse orientation of both planes of both beams. An example of this display is shown in Fig. 4.

Many checks of the transverse and longitudinal wakefields[8,9] in the linac have been made. The measured effects agree with the predictions to within a factor of two. One of the tests is particularly enlightening displaying the fact that the head of the bunch transversely drives the tail of the bunch. The beam is made to oscillate vertically using a dipole near the front of the linac. Thus, vertical wakefield effects should increase the vertical size of the beam. To separate the head from the tail, the bunch was accelerated off the crest of the RF waveform so that the head of the bunch had more energy after acceleration than the tail. The head and the tail were then separated at the end of the linac by bending the beam into the beginning of the arc where there is horizontal dispersion. The beam was viewed by a profile monitor. The image on the screen shows energy horizontally and betatron motion vertically. The experimental setup is shown in Fig. 5. The results are shown in Fig. 6. As the dipole magnet was varied up and down, the head of the beam did not change position very much but the tail, driven by wakefields, moved dramatically and with the same sign as the dipole. Furthermore, it is clear that the particles in each longitudinal 'slice' of the bunch are driven in the same way and no internal growth of emittance in each slice is present. This fits theory very nicely.

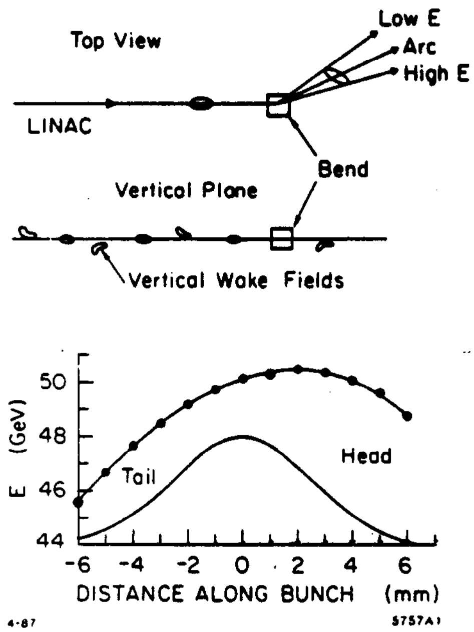

Fig. 5. Experimental setup for wakefield test in Fig. 6.

The launch of both positrons and electrons into the linac from the damping rings and into the arcs from the linac must be controlled with feedback systems. Presently the position and angle of electrons into and out of the linac are controlled once per minute by so-called slow feedback processes. The energy is also controlled once per minute. The processes for positrons are now just starting to be commissioned. A fast feedback on the energy[9] of the electrons operating on a pulse basis has been shown to work well and is now being incorporated in the online control system. Fast pulse-by-pulse feedback on the positron energy and the wakefield induced beam tails is under development. It is expected in the fall.

7. ARCS

The north arc (electrons) has been under continual study since December 1986. The south arc (positrons) has been studied only briefly in March during the two beam collision test.

The goals for the arcs[10] are to transport the SLC beams to the final focus without loss and without increasing the beams' emittances and to provide suitable betatron and dispersion functions at the end which are correctable by finite adjustments in the final focus. Electrons have been transmitted to the

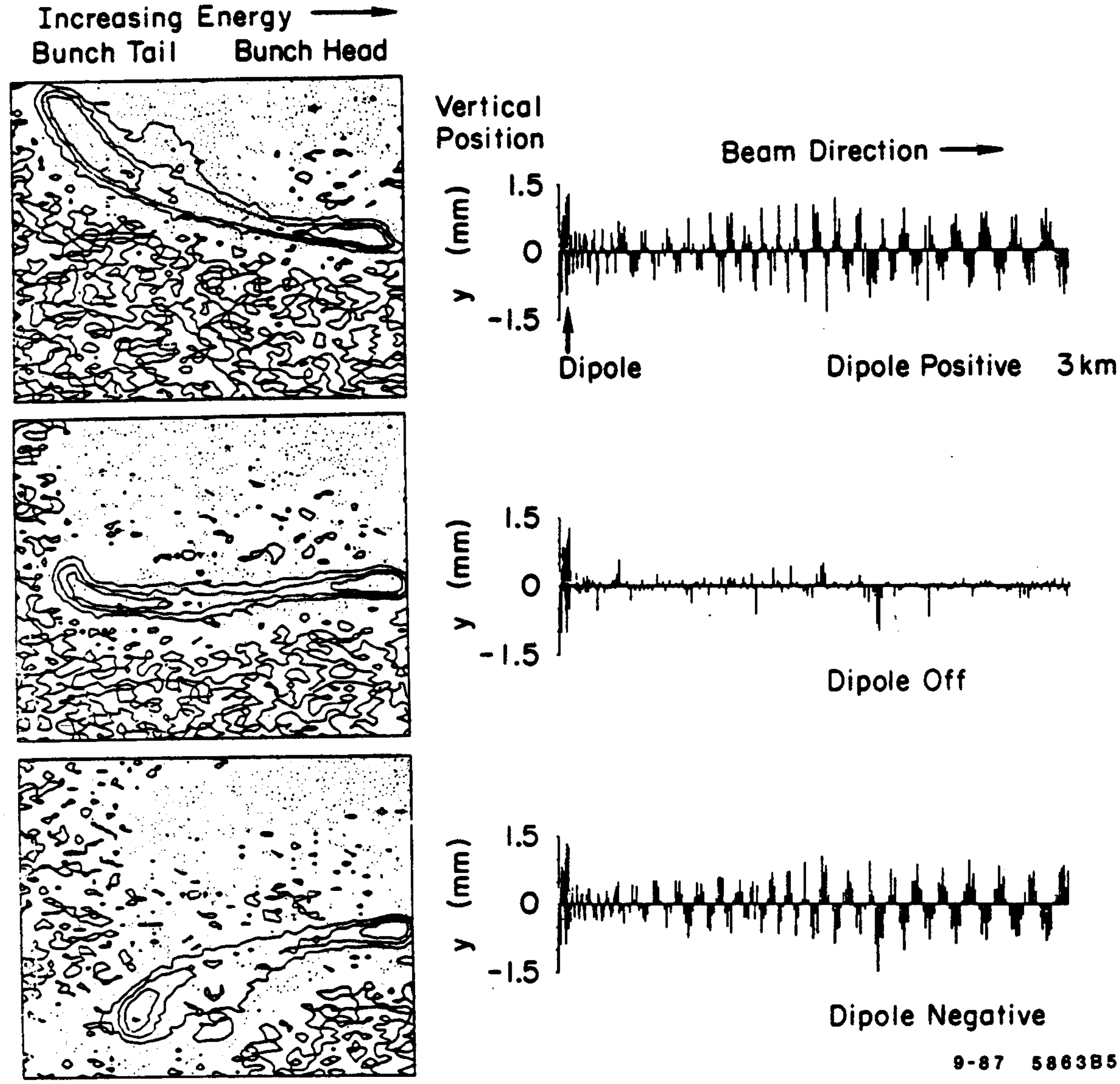

Fig. 6. Experiment demonstrating that the bunch head drives the tail due to transverse wakefields.

final focus without losses as can be seen in Fig. 7, which shows the trajectory and intensity through the north arc after correction. Three hundred micron rms trajectory errors can now be easily achieved.

The goal to provide correctable betatron and dispersion functions has not been met. Part of the problem of the beam mismatch is due to changing conditions in the linac and to magnet alignment problems in the linac-to-arc transition region. However, substantial errors arise from problems in the arcs. Mechanical hysteresis, binding, shaft slipping, and ball and socket alignment problems of the magnet movers make trajectory correction uncertain and irreproducible. Solutions for most of these problems are in hand, and corrections are being made. Some of the beam position monitor cables have intermittent connections which cause non-apparent 3 mm offsets in the readouts. The combination of discrete rolls of the achromats in the arcs (planned) and errors in the phase advance per cell (unplanned) causes horizontal-vertical coupling which mixes the phase space of the beam and can produce betatron amplification. An example of this is shown in Fig. 8 where a vertical mover in achromat N04 was changed to produce a vertical betatron oscillation. After several achromats, a horizontal oscillation appears and grows quite large by the end of the arc. Horizontal to vertical coupling is also observed. The solution

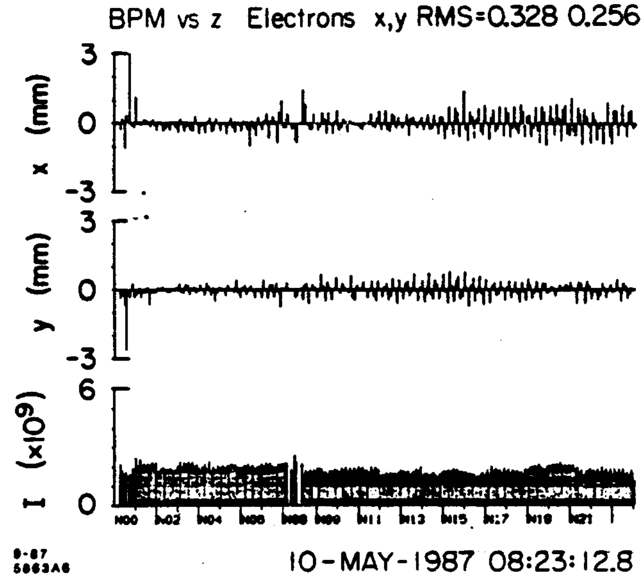

Fig. 7. Electron trajectory in the north arc corrected by an automatic procedure using the magnet movers.

to this problem is to correct the phase advance per cell locally for each achromat. Phase correction is complicated by the sextupole term in the arc magnets and the movement procedure of the magnets but has been successfully applied to several achromats.

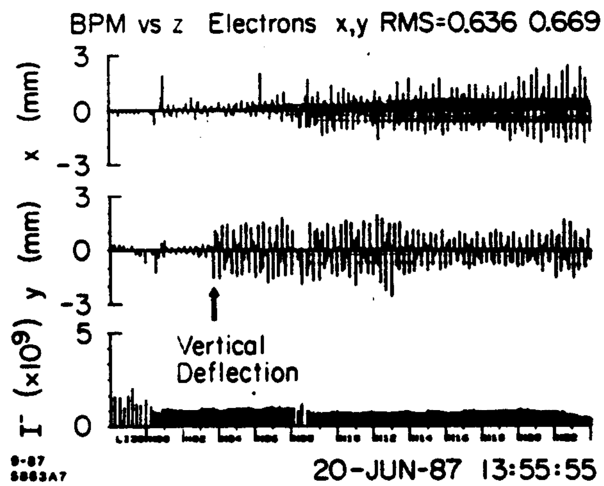

Fig. 8. Betatron coupling in the north arc caused by uncorrected phase advances per achromat.

8. <u>FINAL FOCUS</u>

In February 1987, the installation of the magnets, controls and instruments needed to transport both beams to the collision point was completed. Only a few components required to take the beams to their respective dumps and several collimators remain to be installed. In March, a program was undertaken to accelerate both positrons and electrons and pass them through the collider hall on the same linac cycle. This goal was reached on March 27, 1987, at 4:45 p.m. when 4×10^9 electrons and 4×10^8 positrons passed through each other. A photograph of the two beams as seen on a position monitor at the interaction point is shown in Fig. 9. Both beams had energies of 46 GeV. The beam sizes were too large to make an interesting luminosity, but the event marked the end of the SLC construction.

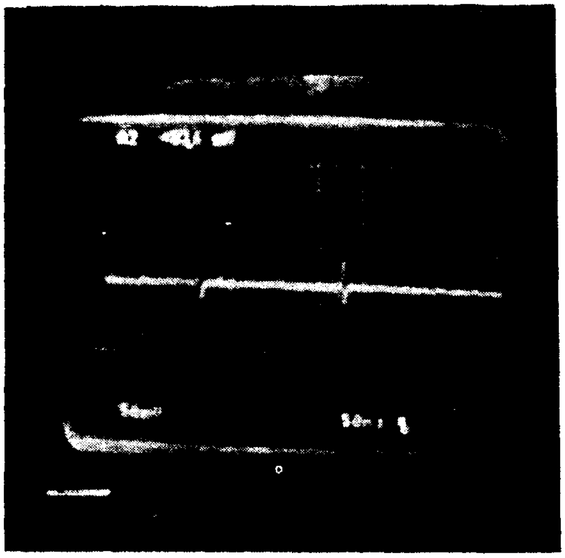

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Fig. 9. Signals on the beam position monitor at the interaction point showing electrons (left) and positrons (right) colliding on the same linac cycle.

The areas of work underway are the reduction of beam induced noise in the beam position monitors, beam trajectory and transmission correction and betatron and dispersion matching of the beam from the north arc. A typical beam trajectory in the later north arc and the final focus is shown in Fig. 10. Studies[11] soon to start include size, angle and chromatic shape corrections of the electrons at the collision point. At present the smallest spot sizes measured are 100 microns horizontally and 30 vertically. A moving wire scanner was used to determine the beam size. These large beams sizes are believed to be caused by mismatched dispersion and betatron functions exiting the north arc.

The present instruments at the intersection point include a screen profile monitor (40 micron resolution), an x-y wire scanner (20 and 7 micron wires), and a position monitor (50 micron resolution). After the MKII is installed, there will be an x-y wire scanner at the IP with seven micron wires, a vertex beam position monitor with about 100 micron resolution, beamsstrahlung monitors for both beams and equipment for measuring beam-beam deflections. Instruments located at low betatron functions outside the immediate collision region to measure the beam shape are under investigation.

9. SLC FUTURE PLANS

The general plan for commissioning the SLC as of June 1987 is to concentrate on electron studies in the north arc and final focus to produce an acceptable beam (size and background) for collisions and, as time allows, to pursue increased positron production, positron intensity in the south damping ring

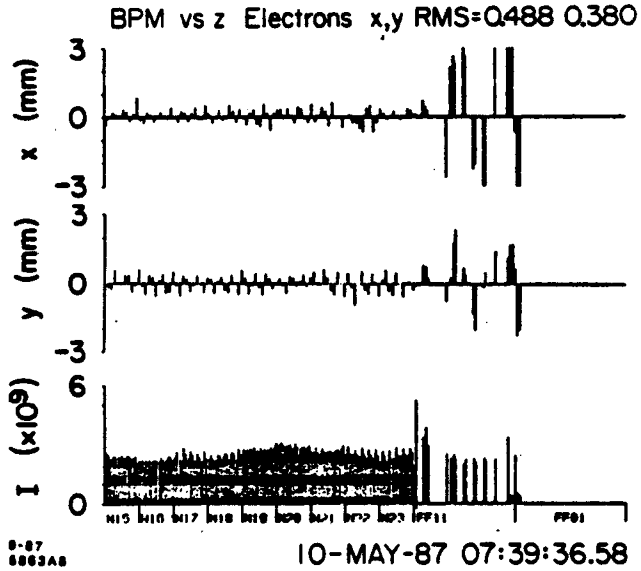

Fig. 10. Electron trajectory in the north arc and final focus.

and two beam trajectory correction in the linac. Studies to provide stable beams through feedback are included as needed by the program.

If all the best parameters so far achieved at the SLC (not measured at the same time) are used to calculate a present possible luminosity, a luminosity of 2×10^{25} cm^{-2} sec^{-1} is calculated. The details of this calculation are shown in Table 3. Three hundred times that luminosity is needed to produce fifteen Z^o per day, the signal point for installing the MKII detector. The parameters needed to achieve 6×10^{27} cm^{-2} sec^{-1} are also shown in Table 1. The main advance must be in the beam cross section. The milestones for achieving this luminosity are 1) to produce a 4 micron beam spot, 2) make 10^{10} particles (e^+, e^-) stable in the linac, 3) align both beams in the interaction region, 4) get high current beams to the collision point, 5) increase the repetition rate to 120 Hz, and 6) reduce beam halo and backgrounds. The expected rate of progress suggests that the detector will be installed in early fall.

Table 3.

Luminosity projections, $\left(\mathcal{L} = \dfrac{N^+ N^- f}{4\pi \sigma_x^* \sigma_y^*}\right)$.

	$N^+ \times 10^{10}$	$N^- \times 10^{10}$	f (Hz)	σ_x^* (μm)	σ_y^* (μm)	$\mathcal{L}$ cm^{-2} sec^{-1}
Possible June 21, 1987:	1	1	60	100	30	2×10^{25}
Expected Fall 1987:	1	1	120	4	4	6×10^{27}

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