TUNING THE ARCS OF THE SLAC LINEAR COLLIDER*

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ABSTRACT

New experience with the operation of the SLC Arcs is described. Each of these Arcs consists of sequential second-order achromats. Initial measurements showed that the betatron phase advances were systematically offset from the design values. This effect, combined with the abrupt rolls of the achromats needed to follow the local terrain, led to strong cross-plane coupling and to growth of the betatron oscillations. The methods and modifications developed to establish proper operation of the Arcs are described.

INTRODUCTION

The SLC Arc system is designed[1] to preserve low emittance beams while transporting electrons and positrons from the end of the Linac to the beginning of the Final Focus System *(FFS)*. This task is made difficult by the strong coupling of transverse oscillations caused by the rolls of the bend planes of the achromats about the beam axis. The rolls were needed to generate vertical deflections to follow the terrain. Figure 1 is a bar graph representing the roll angles about the beam axis for the North and South Arcs. The roll of an achromat with respect to its neighbor is given by the difference in height between corresponding bars in this plot. The design[2] of this system and the initial operating experience[3] have been published. Here we describe recent experience with the Arcs. We begin with the expected and unexpected errors, then discuss the measures designed to deal with them, followed by the procedures and modifications vernacularly known as Phase-fix, Wrench-fix, Rit-fix, Roll-fix and Wire-fix. Finally, we summarize the resulting improvements of the Arcs' performance.

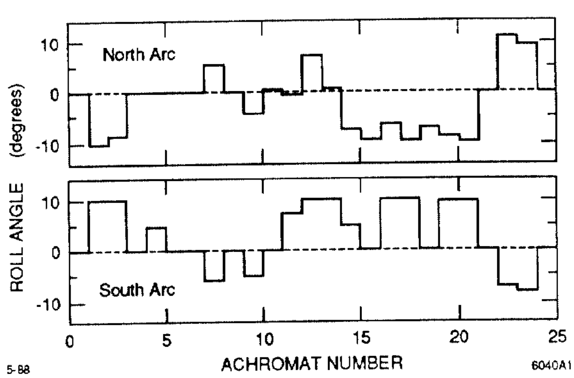

Fig. 1. Roll angle about beam axis versus achromat number for North and South Arcs.

ERRORS AND FAILURES

During the period when the Arcs were being designed, the effects of magnet positioning errors were investigated and tolerances were specified. Both systematic and random translational errors were shown to be important.

Systematic Translations of Magnets

The orbit correction system for the Arcs[4] utilizes the movement of magnets to deflect the beam. Systematic offsets of these magnets having dipole, quadrupole and sextupole field components can generate optical anomalies.[5,6] The causes of such offsets in the horizontal plane can include: a) a systematic error in the horizontal beam position monitor *(BPM)* alignment or signal processing or b) steering a beam which has the wrong energy with respect to the Arc excitation.

This comes about due to the one-to-one correspondence between the offsets of the horizontal magnet movers and the offsets of the BPMs which measure the horizontal beam position, combined with the fact that the matched dispersion function has the same value 35 mm at each such *BPM*. Steering an off-momentum beam with $\triangle P/P = 10^{-3}$ induces a systematic error Δx in the magnet positions of 28 μm which is just detectable. These systematics show up in the harmonic analysis of the magnet mover positions and, in principle, are correctable for magnitudes greater than ~ 30 μm.

Backleg Windings

Another source of systematic horizontal transverse errors is the continuous loss of energy of the beam due to synchrotron radiation. As a particle loses energy its orbit moves radially and any attempt to steer the beam to the central design orbit will generate a systematic offset of all horizontally focusing magnets. This relative difference between the beam energy and the excitation of the magnet is corrected achromat by achromat by use of backleg windings *(BKLG)* around the yoke of each magnet.

F–D Imbalance

The yoke of each Arc magnet encircles only two of the four main aluminum conductors. The horizontally focusing (F) magnets are excited by two of the conductors whereas the defocusing (D) magnets are excited by the remaining two. A bypass circuit called the *F–D imbalance* was provided to allow different excitations for the F and D magnets. The effect of setting the F–D imbalance to a difference value of 1% and resteering the beam is to change the phase advance per cell for the horizontal plane μ_x by $-1.4°$ and for the vertical plane μ_y by $+1.4°$. The F–D imbalance has been tuned to a value of 0.7% for the North (electrons) and 0.0% for the South (positrons) Arcs compared to the 2% value obtained from the magnetic field measurements.

Random Errors

Commissioning experience has demonstrated that the random alignment and field errors are close to the design specifications. For instance, the measured rms value of 200 μm for the positions of the magnet movers after steering agrees with prediction.

Mechanical Failures

The design of the magnet movers required that the feet of the magnet be held by gravity in a cup-shaped support. The pitch of the magnets (in some places greater than 5 degrees) caused the feet to slip out of these cups. An extensive effort which included the welding of longitudinal restrainers, the retrofitting of anti-twist devices and the realignment of the magnets eventually solved this problem.

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ERROR CORRECTION

Phase–Fix

Optical distortions in the Arcs were initially detected as errors in the phase advance of induced betatron oscillations accompanied by amplitude growth of nearly a factor of three. Just as the systematic offsets of the horizontally focusing magnets can induce first-order optical distortions such offsets can also be used to correct at least part of such distortions. The process of adjusting the betatron phase advance in each achromat became known as *Phase-fix* and used the systematic horizontal offset of the F magnets relative to the D magnets to cause this optical change. The procedure consists of three steps: first, the phase advance was determined for both planes in each achromat by inducing, measuring and fitting betatron oscillations. Next, the backleg windings were used to change the excitation of the magnets of a particular achromat by a calculated amount relative to the beam energy. Finally, the beam was steered to produce a systematic horizontal offset of all F magnets. The magnitude of these changes can be seen by assuming a change in magnet excitation equivalent to $\Delta P/P = 10^{-2}$. As shown this will induce a systematic error Δx in the magnet horizontal positions of 280 μm. The sextupole component of the field causes a corresponding change of $\Delta\mu_x$ of $-0.7°$ and $\Delta\mu_y = -2.0°$. The main conductors carry a current I of 3670 Amps to operate at 47 GeV; therefore this excitation change requires 1.26 Amps in the 29 turns in each of the two backleg windings. Thus the formulae used were $\Delta\mu_x = -0.55\delta I_{BKLG}$ and $\Delta\mu_y = -1.6\delta I_{BKLG}$ with a resulting offset given by $\Delta x = (280/1.26)\delta I_{BKLG}$. The F–D imbalance was used once for a global adjustment affecting the entire Arc.

Wrench–Fix

As shown in Fig. 2(a) the initially measured phase advances μ_x and μ_y in the first half of the South Arc were too small. Using the formulae above it was determined that a magnet offset $\Delta x \sim 800$ μm would be needed for correction. An alignment procedure was used which became known as *Wrench-fix.* Both ends of all magnets were moved horizontally by 200 μm to bring the neutral pole of each closer to the beam line. Since the horizontal magnet movers shift only one end of an F magnet, this procedure is equivalent to offsetting all such movers by an amount four times larger. The resulting phase advances are shown in Fig. 2(b).

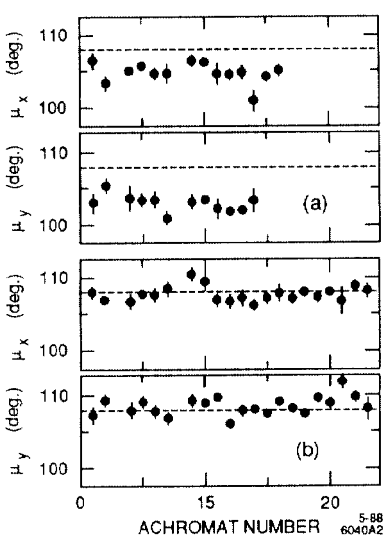

Fig. 2. Phase advances per cell in South Arc before (a) and after (b) correction.

Dispersion Correction

Alignment errors in the Beam Switchyard *(BSY)* between the linac and the Arcs were determined to be a cause of errors in the initial conditions of the Arc dispersion functions η_x and η_y. The expression $\Delta\eta_x = x_o T_{116} + \theta_o T_{126}$, where x_o and θ_o are position and angle errors at a given point in the BSY and T_{116} and T_{126} are the corresponding second-order transfer matrix elements to the Arcs, illustrates such a first-order deviation due to second-order terms. Transverse alignment errors of the order of 1 mm can change the value of the dispersion function at the entrance to the Arcs by 25%. These errors were found and corrected.

IMPROVEMENTS

Rit–Fix

Errors in the dispersion can also be created by optical errors in the presence of coupling. Though the matched dispersion function is not directly affected by gradient errors of the order of several percent (which would change the phase advance per cell by several degrees) such errors do generate anomalous dispersion in the presence of the coupling due to rolls. It was found that this coupling can be suppressed by rolling the last defocusing magnet in the preceeding achromat by an angle equal to one half of the roll angle of the following achromat. The reference orbit can be kept unperturbed by a small vertical offset of the magnet. This maneuver is referred to as *Rit-fix* after its author.[7] Figures 3(a) and 3(b) show the dispersion in the North Arc before and after this correction. Note that in the North Arc the dispersion had already been corrected to the design value, but it was still advantageous to reduce the effect of quantum fluctuations by the suppression of the vertical dispersion.

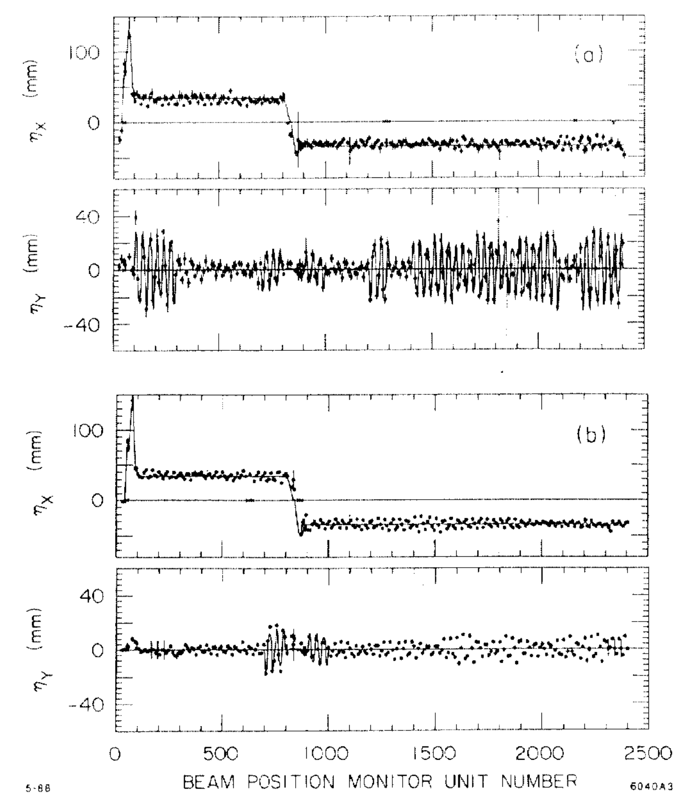

Fig. 3. Measured dispersion in North Arc before (a) and after (b) application of Rit-fix. Solid lines are theoretical functions.

Roll–Fix

The demonstration that rolling a single D magnet would suppress the vertical dispersion suggested that rolling individual magnets might also suppress coupling of betatron oscillations. The first such suggestion[8] divided each single roll of angle θ_0 into three parts, θ_1, θ_2 and θ_1, as shown in Fig. 4(a). The symmetry and magnitudes of the rolls θ_1 and θ_2 can be made understandable by considering each roll as being represented by a two-dimensional vector the length of which is proportional to the magnitude of the roll angle and with the polar angle between the three vectors equal to the phase advance per cell of 108°. The vector sum of the three is constrained to be zero and the sum of their magnitudes equal to θ_0. This uniquely defines the value of the ratio $r = \theta_1/\theta_0$ to be 0.382 and $\theta_2/\theta_0 = 1 - 2r$. The D magnet in each cell is then rolled by half of the roll of the cell resulting in the relative rolls as indicated by the upper downward pointing arrows.

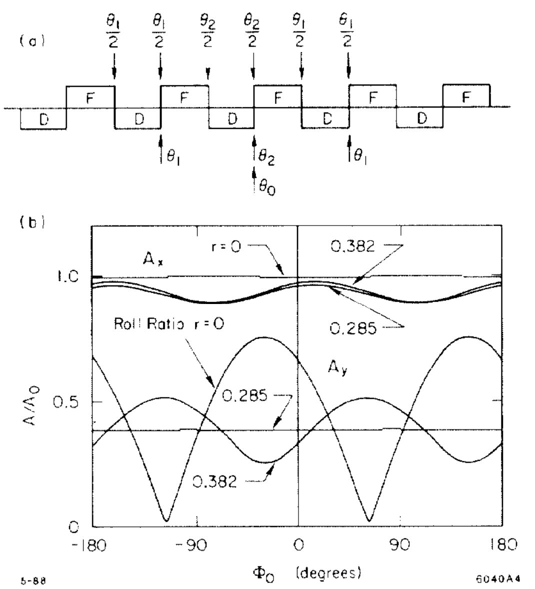

Fig. 4. (a) Typical redistribution of roll angles. (b) Cross coupling versus Φ_0 for various values of r.

Figure 4(b) illustrates the calculated[9] cross-coupling effects using the lattice transfer matrices for various values of r. A betatron oscillation of amplitude A_0 in the horizontal plane crosses a boundary between achromats which are rolled by $\theta_0 = 10°$ with respect to each other. The normalized amplitudes A_x and A_y of the resulting oscillations in the downstream achromat are plotted versus the phase angle Φ_0 of the input oscillation at the boundary.

Consider the case where $r = 0$, i.e., the roll has the initial design value. It can be seen that the amplitude A_y of the oscillation in the vertical plane can vary from near zero to $\approx 0.75A_x$ depending on the phase Φ_0. In order for this oscillation to be cancelled by a roll of $-10°$ at the next boundary the phase relationship between the two oscillations must be preserved. Errors in the relative phases will result in incomplete cancellation and residual cross-plane coupling. The case where $r = 0.382$ is also shown and it is apparent that the magnitude of the vertical oscillation is less influenced by the input phase. Finally, for $r = 0.285$ the amplitude of the vertical oscillations become independent of the phase angle of the incoming oscillation and hence less susceptible to phase errors. Not shown here is the behavior of the phase of the induced vertical oscillation which becomes linear in Φ_0 only for $r = 0.285$, further reducing the susceptibility to phase errors.

The Arc boundaries with rolls greater than 8° were modified to correspond to $r = 0.382$ in the North and $r = 0.285$ in the South Arcs.

Wire–Fix

Besides systematic gradient changes (zeroth harmonic), coherent gradient deviations at the second harmonic of the betatron frequency are also used for tuning the Arcs. This is done by isolating four out of 29 turns of the backleg windings in the last seven achromats of each Arc. Thus two new coils (upper and lower) are created for each magnet. The coils of every tenth magnet are connected in series making 20 circuits powered independently. The power supplies are computer controlled to drive eight almost orthogonal knobs. This will create cosine- and sine-like regular and skew harmonic perturbations in each plane to control the betatron oscillation growth and the coupling between the planes.

PERFORMANCE OF THE ARCS

Overall Transfer Matrix

Data obtained by inducing betatron oscillations using correction magnets in the linac have been analyzed[10] to determine the 4×4 coupled transfer matrix to selected areas in the FFS. At a chosen BPM the coupled linear response to individually applied deflections from four horizontal correctors and four vertical correctors was measured. These 16 measurements along with the ideal known transfer matrices between the eight linac correctors provided constraints to find a solution for the transfer matrix between the linac and the BPM. The symplectic conditions were satisfied by varying the measured values within their errors. Dispersion data were included to generate a 6×6 transfer matrix which agreed with the oscillation and the dispersion measurements to within 1σ of the measurement errors. The final transfer matrix when combined with profile monitor data was used to compare measured beam parameters in the linac and FFS.

The evaluated emittance growth in the Arcs is small and acceptable for achieving small spots at the Interaction Point.

Comments on Performance

The beams are stable and reproducible. No major magnet failures have occurred. All special quadrupole and bend magnets are operating at the design values. Random alignment and field errors are within specifications. Systematic transverse magnet displacements are controllable.

CONCLUSION

At present, both Arcs are operational and deliver acceptable electron and positron beams. Ongoing work is now aimed at minimizing background at the interaction point by improving collimation and optical adjustments.

ACKNOWLEDGEMENTS

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REFERENCES

[1] SLC Design Handbook, Stanford Linear Accelerator Center, December 1984.

[2] S. Kheifets et al., *Proceedings of the Thirteenth International Conference on High Energy Accelerators*, Novosibirsk, USSR, v. 1, 168 (1987).

[3] G. Fischer et al., *Proceedings of the Twelfth Particle Accelerator Conference*, Washington, D.C., v. 1, 139 (1987).

[4] J. J. Murray, unpublished.

[5] T. Fieguth et al., *Proceedings of the Twelfth Particle Accelerator Conference*, Washington, D.C., v. 1, 77 (1987).

[6] W. T. Weng and M. Sands, *Proceedings of the Twelfth Particle Accelerator Conference*, Washington, D.C., v. 2, 1221 (1987).

[7] D. Ritson, unpublished.

[8] P. Bambade, SLAC-PUB-4610, April 1988.

[9] M. Sands, unpublished.

[10] T. Barklow, unpublished.