© 1989 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

PHASEFIX–CORRECTING THE TUNES OF THE SLC ARCS*

J. Haïssinski,[a] P. Bambade,[a] K. L. Brown, D. L. Burke, T. H. Fieguth, A. Hutton, T. Mattison, J. J. Murray, N. Phinney, M. Placidi,[b] M. Sands, J. C. Sheppard, N. Toge and A. Weinstein[c]

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

ABSTRACT

The betatron phase advance in the SLC ARC beam transport line is sensitive to gradient errors in the magnetic lattice. The systematic errors in the phase advance, combined with the rolls required to follow the terrain, can lead to xy-coupling which significantly distorts the betatron phase-space. The technique used to measure and correct the tune of the Arcs is reported.

1. INTRODUCTION

The SLC North and South Arcs transport the electron and the positron beams, respectively, from the end of the linac to the beginning of the Final Focus Section (FFS). Their optical design[1] has been optimized to preserve the low emittance of the input beams. The North (South) Arc is comprised of 23 (22) second-order achromats with some special sections inserted. Each achromat has 10 identical FODO cells, each with two combined function magnets having dipole, quadrupole and sextupole fields. This produces a betatron phase advance of 108° per cell (6π per achromat) for both the horizontal (x) and vertical (y) planes.

For the purpose of orbit corrections, each horizontally focusing magnet (F) can be displaced horizontally with a magnet mover (XMOV) to steer the orbit of the beam at a position monitor (BPM) placed immediately in front of the corresponding F magnet in the next cell downstream. An identical and interleaved system for correcting the vertical orbit uses the horizontally defocusing magnets (D) with vertical movers (YMOV) and corresponding BPMs for measuring the vertical offset. The BPM readout system is presently designed to detect a transverse offset in only one plane or the other. The BPMs are installed at every intermagnet drift where $\beta_x = \beta_y \approx 4$ m and $d\beta_x/ds = -d\beta_y/ds$, so the measured displacement differences for a betatron oscillation of constant amplitude is due to phase advance differences only.

Generally the achromats in an Arc are not coplanar. Many are "rolled" around the beam axis to provide vertical deflections to follow the site terrain. These rolls cause local xy-coupling between the betatron oscillations which in an *ideal* system would be eliminated overall. However, in the presence of *gradient* and hence *phase advance errors* this coupling can accumulate. For the Arcs *systematic gradient errors due to systematic transverse offsets in the sextupole field* of the combined function magnets were found to be especially troublesome.[2] Correction required measuring the phase advance of the betatron oscillations achromat by achromat and applying *systematic horizontal position corrections and excitation corrections.* This process is called *PHASEFIX*.

2. ROLLED ACHROMATS AND BETATRON OSCILLATIONS

Figure 1 shows the roll angles for the achromats in the North and South Arcs. Many achromats are rolled as much as 10°. Consider the effects of such a roll (of angle θ) on the motion of a particle which is undergoing a purely horizontal oscillation with amplitude A_x before crossing the roll boundry. Because of the coupling, the oscillation downstream of this roll will have both x and y components. The amplitude in the y plane can be written[3] $A_y = MA_x \mid \sin\theta \mid$ where M is a "magnification factor" which depends on the betatron phase Φ_x of the initial oscillation at the roll boundry (see Fig. 2). The M can take a value as high as 5.5, so that $M \sin\theta$ where $\theta = 10°$ is then close to unity, *i.e.*, the induced y plane oscillation can be as large as the x plane oscillation.

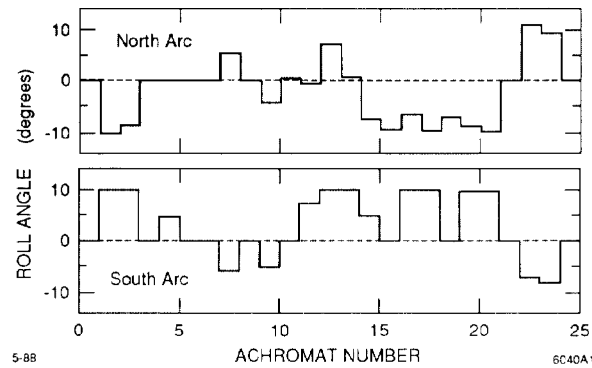

Fig. 1: Roll angle about the beam axis vs. achromat number for North and South Arcs.

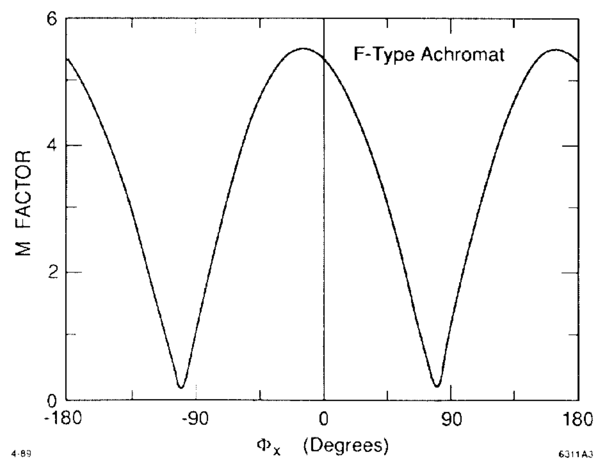

Fig. 2: Cross-coupling M factor vs. phase Φ_X at roll boundary.

Figure 3 illustrates how this magnification occurs. Here, ellipse a_0 represents values for x vs. dx/ds for an oscillation of arbitrary but constant amplitude A_x at the rolled boundry between achromats. A particular oscillation is represented by its polar coordinates ($A_x\sqrt{\beta_x}$, Φ). Ellipse b_0 represents oscillations of the same amplitude but in the y plane. It is a reflection of the first ellipse about the vertical axis because at the boundary a relationship holds: $\beta_x = \beta_y$ and $d\beta_x/ds = -d\beta_y/ds$. We consider a particle oscillating in the horizontal plane with a betatron phase such that its motion *at the roll* is represented by the point P_{x0}. After the roll, *i.e.*, at the entrance of the next achromat, the points P_{x1} and P_{y1} represent the x and the y oscillations, respectively. Here $\overline{OP}_{x1} = \cos\theta\ \overline{OP}_{x0}$ and $\overline{OP}_{y1} = \sin\theta\ \overline{OP}_{x0}$. Thus the ellipses ($a_1$) and ($b_1$) represent the x and y oscillations of nearly equal amplitude in the achromat downstream from the roll.

If at the end of the following achromat the roll is removed, and if the phase tune of the achromats is perfect, then the inverse

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

(a) Laboratoire de l'Accelerateur Lineaire, Orsay, France.

(b) CERN, CH-1211 Geneva 23, Switzerland.

(c) California Institute of Technology, Pasadena, California, USA.

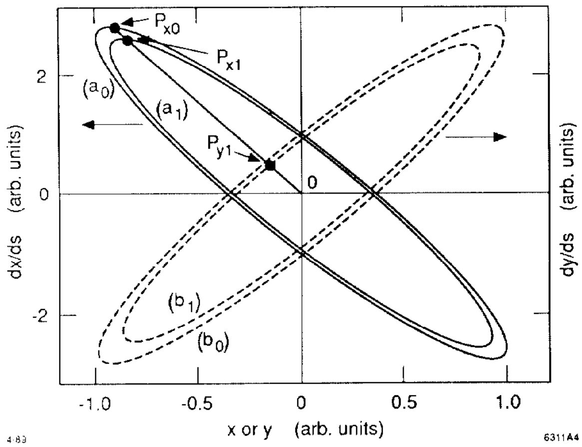

Fig. 3: Coupling of oscillations at roll boundary.

of the above process will cancel the induced vertical oscillation. As shown in Fig. 1, the net roll is zero overall in the Arcs, and at many intermediate points. If, however, there exists an error causing the phase advance in the achromat to deviate from 6π, then at the exit Φ_x, and hence M will differ from the entrance values and the cancellation will be incomplete. The deviations of the phase advance from its design value can result in an accumulation of crossplane coupling. Simulations have shown[4] that this accumulated crossplane coupling can cause a growth in the effective emittance of the beam. An example of this growth is illustrated in Fig. 4, where the horizontal beam size along the North Arc is shown, for a systematic error of 3° in the phase advance per cell in each plane.

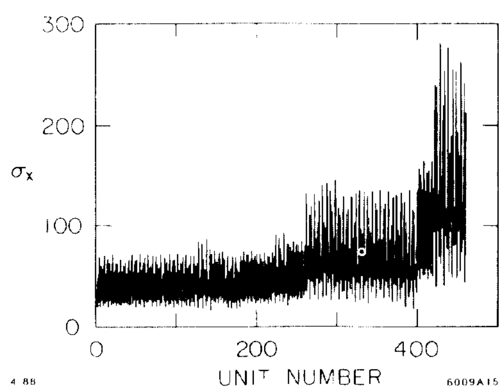

Fig. 4: Beam growth in North Arc, for systematic erros of 3°/cell in each plane.

3. INITIAL PHASE MEASUREMENTS

When the North Arc was commissioned[5] in Spring 1987, the phase advance in the Arcs were measured as one of the first planned experiments. The results showed that the average phase advances per cell μ_x and μ_y differed by equal and opposite amounts, respectively, from the design value (108°/cell). This type of error was not unexpected and was symptomatic of a systematic difference in the magnitude of the gradients of the F and D magnets. Provisions have been made to differentially adjust the excitation currents of all F and all D magnets in each Arc as a group (F–D imbalance). Calculations show that setting the F–D imbalance to a difference value of 1% and resteering the beam changes the phase advance per cell for the horizontal plane μ_x by $-1.4°$ and for the vertical plane μ_y by $+1.4°$. This was experimentally confirmed.

Though the gross phase advance errors initially noticed were corrected, it was observed that the horizontal and vertical dispersion still did not follow the expected pattern. Similar deviations were observed for the horizontal and vertical betatron oscillations, and growth of the projected emittances along the Arcs was inferred. Most of these observations were ascribed to errors, which could be detected and compensated for by their effect upon the phase advance. A systematic correction of the phase advance, achromat by achromat was undertaken. In this phase, advance in each plane in each achromat was first measured; then both brought as close as possible to their common design value of 108° per cell by a single adjustment. The adjustment made use of the horizontal magnet movers XMOV and consisted of a horizontal transverse displacement of all F magnets within the achromat by the same calculated amount. An offset of +1.0 mm of all such magnets will change the horizontal phase advance per cell $\Delta\mu_x$ by $-2.5°$ and the vertical $\Delta\mu_y$ by $-7.1°$. The resultant transverse offset of the orbit was then corrected back to the design trajectory by adjusting the excitation of all magnets in the achromat. This was done using the power supply (one to each achromat) connecting in series the "back-leg" trim windings of all magnets in an achromat. This circuit was included in the design to allow matching the excitation to the local energy of the beam as it loses energy to synchrotron radiation.

This method proved to be successful in correcting the phase advances, though it has not been determined exactly at which stage of the construction those gradient errors had been introduced.

4. PHASE ADVANCE MEASUREMENT

Several techniques have been used to determine the *total* phase advance over each achromat. The first consists of exciting a betatron oscillation by moving one of the magnets in the Arc and fitting a sinusoid (see Fig. 5) to the 10 measured offsets in an achromat. The curve which is fitted is

$$M(j+n,j) \;=\; a\sin\left(\phi_0+(n-1)\mu\right)$$

where the amplitude a, the initial phase ϕ_0 and the average phase advance per cell μ are fitted parameters. $M(j+n,j)$ is the beam displacement in the $(j+n)^{th}$ BPM caused by the j^{th} XMOV. Data points corresponding to small displacements are more constraining than those which are close to a sinusoid extrema. Thus this determination of μ is biased and may not represent a properly weighted average for the whole achromat. Comparing two measurements with differing initial phases partially removes this bias. Many alternate methods were also tried to improve the accuracy of the measurements. The method finally adopted was one in which overall consistency was demanded. The orbit in the next achromat downstream was included in the fit and it was required that the value for its phase at the boundry agree with that calculated using the fitted parameters for the achromat being measured. The estimated error for the phase advance *per cell* is 0.5°.

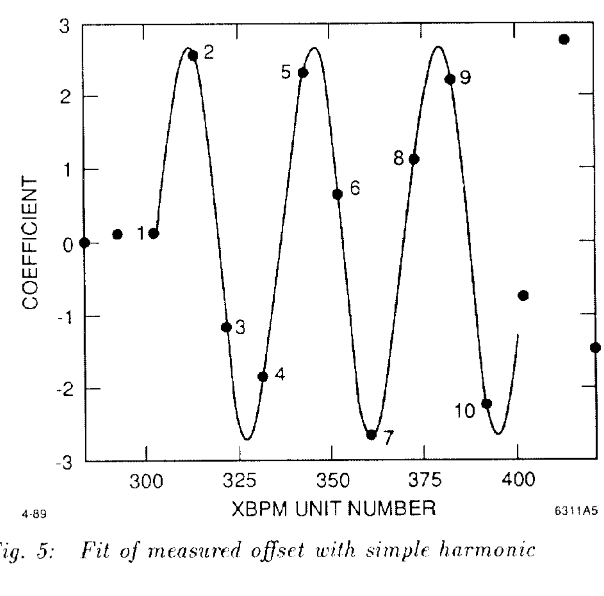

Fig. 5: Fit of measured offset with simple harmonic

The amplitude and phase can also be examined cell by cell in a manner which can show local tune errors. This method is illustrated in Fig. 6, which shows data collected *before* the completion of a full phasefix. Consider a pair of BPMs labelled i and $i+1$, which are apart by one cell only, and write: $x_i = a_i \sin(\phi_i)$ and $x_{i+1} = a_i \sin(\phi_i + 108°)$. These equations are solved for a_i and the phase ϕ_i representing the local oscillation. Note in Fig. 6 that amplitude growth is clearly seen along with expected amplitude discontinuities at certain rolled boundries. The errors in phase measurement are large where the amplitude is small.

5. RESULTS OF CORRECTIONS

Figure 7(a) shows the results of the phase advance per cell (average value over each achromat) as measured in the South Arc before applying any correction. One notices both systematic and random errors which, in some cases, are larger than 1°. Such errors translate to phase slips larger than 10° per achromat. Both the systematic and the random deviations appear to be significantly larger than what was expected and their origin is not yet fully understood. This was corrected (WRENCHFIX) by realigning all magnets, both F and D, with their neutral poles closer to the beam. Figure 7(b) shows the effectiveness of these corrections.

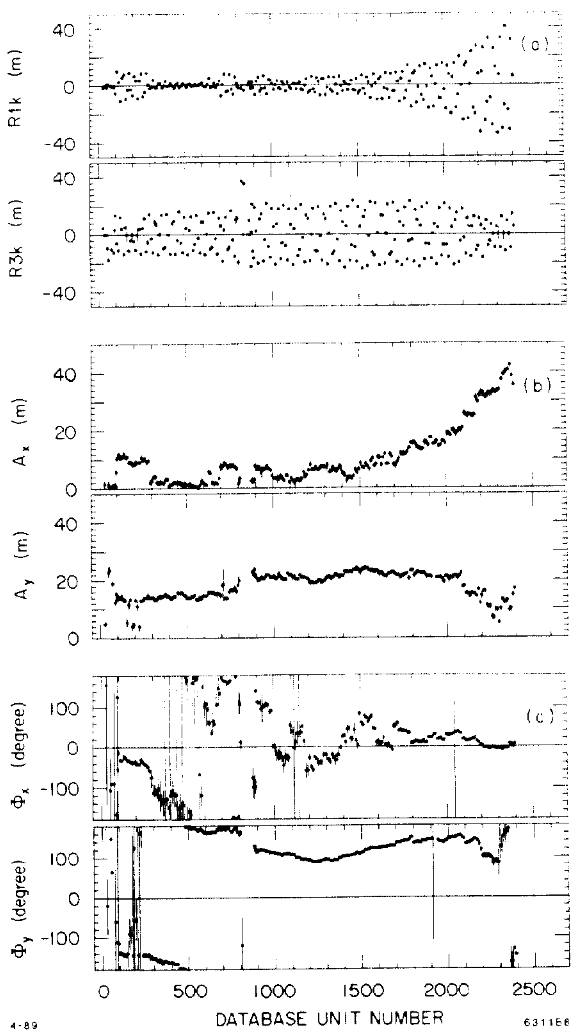

Fig. 6: Betatron oscillation in North Arc: (a) measured displacement; (b) fitted amplitude; and (c) fitted phase.

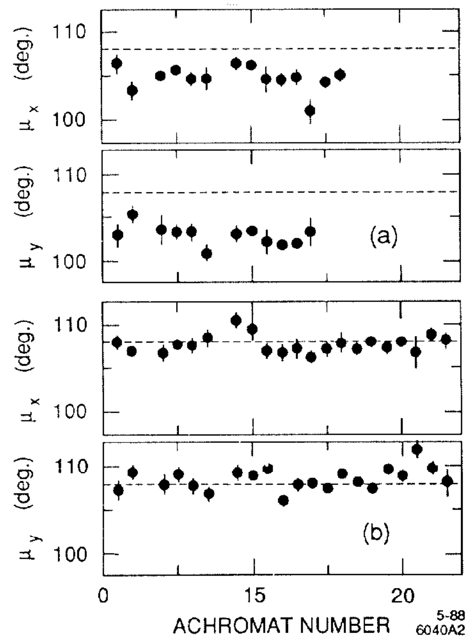

Fig. 7: Phase advances per cell in South Arc before (a) and after (b) correction.

6. SUMMARY

The betatron phase advance tunes are crucial parameters in the SLC Arc optics because of the strong cross coupling between the x and y phase spaces, which takes place at rolled achromat boundaries. Phase measurements have been performed with an accuracy of about 0.3°/cell and, initially, substantial deviations from the design (108°) were observed. Corrections on an achromat-by-achromat basis have been performed to reduce the phase errors within less than 1°/cell. It was done (1) by adjusting a current imbalance between F and D magnets, and (2) by changing the horizontal relative displacements of F and D magnets using the XMOV magnet movers or with re-alignment work.

This action, together with other corrections[4,6,7,8,9] limited the growth of the projected phase space through the Arcs to less than 20%.

REFERENCES

1. S. Kheifets *et al., Proc. of the 13th International Conf. on High Energy Accel.*, Novosibirsk, USSR, v.1, 168 (1987).
2. T. Fieguth *et al., Proc. of the 12th Particle Accel. Conf.*, Washington, D.C., v.1, 77 (1987).
3. M. Sands, *Betatron Oscillations and Rolled Achromats*, SLAC-CN-355 (February 1987).
4. P. Bambade *et al., ROLLFIX- ...*, SLAC-PUB-4835 (February 1989).
5. G. Fischer *et al., Proc. of the 12th Particle Accel. Conf.*, Washington D.C., v.1, 139 (1987).
6. T. Fieguth *et al.*, SLAC-PUB-4628, contributed talk, *European Particle Accelerator Conf.*, Rome, Italy (June 1988).
7. N. Toge *et al., Recent Commissioning Experience on the SLC Arcs*, these proceedings.
8. P. Bambade and A. Hutton, *WIREFIX- ...*, SLAC-CN-370 (February 1989).
9. T. Barklow, *A Technique of Measuring the 4 × 4 Transfer Matrix for Beamline Section with Cross-Plane Coupling*, SLAC-PUB-4969 (April 1989).