forced out of the beam pipe after going through less than a few attainable magnet alignment (-200 pm rms), the beams are achromats, unless a beam steering device is introduced. This is perfectly tuned.

forms a unit beam transfer matrix, if individual achromats are other to provide the required vertical deflections. In several locations roll angles reach up to 10°, but by the Arc exit the total roll angle returns to 0 (zero), insuring that the whole Arc consists of 23 (22) such achromats, with a few matching sections. The North (South) Arc consists of a very strong focusing FODO array of combined function magnets (B ≈ 6 kG, dB/dx ≈ 7 kG/cm) with sextupole components (d²B/dx² = 1.6 kG/cm² for F, -2.7 kG/cm² for D). Each F-D cell produces a phase advance of 108° in both x and y planes. Ten cells are grouped to form a second-order achromat (6° total phase advance). The purpose of the Arcs is to bring high-energy (~ 47 GeV), high-current (> 1 x 10¹⁰ particles per pulse) bunches of electrons and positrons from the SLAC linac to the Final Focus (FF) sections of the SLC, without significant emittance dilution. Here we summarize only the pertinent design parameters: the Arcs consist of a very strong focusing FODO array of combined function magnets (B ≈ 6 kG, dB/dx ≈ 7 kG/cm) with sextupole components (d²B/dx² = 1.6 kG/cm² for F, -2.7 kG/cm² for D). Each F-D cell produces a phase advance of 108° in both x and y planes. Ten cells are grouped to form a second-order achromat (6° total phase advance). The North (South) Arc consists of 23 (22) such achromats, with a few matching sections.

A beam position monitor (BPM) is fixed on each magnet, reading out the x (y) coordinate of the beam position relative to an F (D) magnet entrance. The matched horizontal dispersion function at each BPM is 35 mm and the beta function is 4.2 m for both x and y. The beam pipe aperture is 12 mm (diameter), while a typical transverse beam size in the Arcs is 30 ~ 60 pm.

Since the Arc tunnels are not in a plane, but rather follow the SLAC site terrain, achromats are rolled with respect to each other to provide the required vertical deflections. In several locations roll angles reach up to 10°, but by the Arc exit the total roll angle returns to 0 (zero), insuring that the whole Arc forms a unit beam transfer matrix, IF individual achromats are perfectly tuned.

3. BEAM STEERING

Because of the very high field gradient, with even the best attainable magnet alignment (~200 pm rms), the beams are formed out of the beam pipe after going through less than a few achromats, unless a beam steering device is introduced. This is conveniently achieved with a magnet mover (MOV) mechanism which moves the front end of each F (D) magnet horizontally (vertically) in the range of ±1 mm. A MOV motion of 0.1 mm causes an orbit shift of 0.27 mm as measured by the BPM on the next cell.

Steering using the MOVs works very well. Figure 1 shows the orbit after the steering was done. Except for the matching sections where the steering is only empirically established, the rms orbit deviations in x and y are maintained at ±0.3 mm. As a side-product, diagnoses of various types of hardware problems (BPMs and gross alignment errors) are obtained on a cell-by-cell basis. From the rms variation of MAG MOV setting around the average, after finishing the steering, one can infer the original alignment error to be ~150 pm (see Fig. 2).

Fig. 1: The measured orbit of the electron beam in the (a) North Arc and (b) South Arc on March 10, 1989.

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upright or skew-quad fields due to the magnet placement errors, classes of significant systematic errors remained:

The alignment of the magnets and of the BPMs included these results. In spite of those efforts, and in hindsight, we believe that after the completion of construction, three offsets of effective magnetic center lines (z and y) of each Arc magnet were measured and tabulated. Measurements of BPM centers were also tabulated. The alignment of the magnets and of the BPMs caused optical errors. Careful preparatory work was made in the system at a set of different initial phases. The first method was a simple sinusoidal fitting to the perturbed orbit; eventually it evolved into a full reconstruction of 4 x 4 transfer matrices at every BPM in the system. Various "fix" techniques to apply corrections. Some of them exploited the existing hardware (phasefix, skewfix), others were realized by hardware modifications (rollfix, wirefix). A convenient formalism to characterize the magnitude of "detC". This helped to signify "where we are" at each stage of optical corrections.

4. HARDWARE ISSUES

Since the Arcs consist of combined function magnets with sextupole field components, errors in magnet placements would cause optical errors. Careful preparatory work was made in the construction phase of the project. The offsets of effective magnetic center lines (x and y) of each Arc magnet were measured and tabulated. Measurements of BPM centers were also tabulated. The alignment of the magnets and of the BPMs included these results. In spite of those efforts, and in hindsight, we believe that after the completion of construction, three classes of significant systematic errors remained:

1. The systematic difference of field strength between the D and F magnets at the point of equal gradient was measured to be +2% in the factory test, but found to be +0.7% in the field.

2. Systematic magnet placement errors in x (≈ 400 μm), most likely due to errors in measurements or calculations of x magnetic center line offsets throughout the Arcs.

3. Systematic beam steering errors in y (≈ 200 μm), most likely due to instrumental difficulties in measurements of BPM y offsets relative to the magnets.

The alignment work itself, long range and magnet-to-magnet, appears to have met the goal, except for a few anomalies whose impacts are still being investigated.

5. OPTICAL PROBLEMS

Systematic gradient errors in the Arcs, either in the form of upright or skew-quad fields due to the magnet placement errors, give rise to an undesirable growth of projected beam emittances. This is because the net sum of x-y coupling through the rolled achromat boundaries would cancel only when each achromat is well-tuned. The cancellation is easily broken down by systematic tune errors. Random gradient errors result in similar effects.

Although a growth of projected emittances does not mean a blow-up of the beam emittance in the Liouville's sense, it is serious enough to impede smooth operation of the SLC:

1. The beam ellipse at the linac exit, even if it fulfills the design criteria, does not translate to the output beam ellipse at the Arc exit as designed. This causes a problem in the beam collimation within the FF section, since its arrangement of fixed and variable collimators works properly only for beams that are not seriously mismatched.

2. A small steering change at the linac exit causes a large spatial variation of the beam centroid at the FF entrance.

3. A small fluctuation in the dispersion matching at the linac exit—beam switch yard region translates to a significant change of the beam dispersion into the FF.

Correcting the offset errors based on the construction data was a practically impossible task. Therefore, our approach has been either (i) to apply empirical corrections to particular symptoms, or (ii) to modify the system so that it becomes less vulnerable to mechanical errors. Several important ingredients in the effort are noted:

1. Techniques to measure the beam transport characteristics by generating and observing betatron oscillations through the system at a set of different initial phases. The first method was a simple sinusoidal fitting to the perturbed orbit; eventually it evolved into a full reconstruction of 4 x 4 transfer matrices at every BPM in the system.

2. Various "fix" techniques to apply corrections. Some of them exploited the existing hardware (phasefix, skewfix), others were realized by hardware modifications (rollfix, wirefix).

A chronological description of the development is as follows:

In August 1987, a correction scheme for gradient errors (phasefix) due to horizontal magnet alignment errors was developed. In the North Arc, it helped to achieve ~ 7 μm electron spot size at the interaction point (IP). A similar correction was applied to the South Arc in September 1987. During Winter 1987, modifications were made to the alignment of magnets in the rolled boundaries (rollfix) to smooth out the abrupt roll transitions. This was to make the optical behavior of the Arcs much less vulnerable to systematic gradient errors in the system.

In Spring 1988, a modification to the magnet excitation system was made (wirefix). A variable harmonic modulation of gradient (equivalent to either upright or skewed quads) across one-third of each Arc was introduced, so the effective beta functions of the system are quickly modified, without any realignment work. The Arcs then were functioning well enough to allow FF sections to routinely produce 5–10 μm spot sizes for both electrons and positrons at the IP.

During Fall and Winter 1988, significant progress was made in understanding the x-y coupling, which, formerly, could not be entirely accounted for by the known rolled boundaries. It led to a concept of "skewfix" which corrects for the skew quad components of the magnets which are systematically misaligned in the y (vertical) direction.

See Table I for a list of "fix" actions and references. The net result of those efforts is as follows:

1. A 100% beam transmission through both Arcs is routine.

2. The dispersion has been matched by adjusting the beam steering through the beam switch yard region. See Fig. 3.
Table 1.

<table>
<thead>
<tr>
<th>Action</th>
<th>Variable</th>
<th>Fight against</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phasefix</td>
<td>Horizontal MOVs or z-alignment,</td>
<td>Systematic grad. error / horizontal</td>
<td>8</td>
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<tr>
<td></td>
<td>and F-D imbalance, backleg excitation</td>
<td>magnet offsets</td>
<td></td>
</tr>
<tr>
<td>Rollfix</td>
<td>Adiabatic smoothing of rolled junction</td>
<td>Big variation of x-y coupling</td>
<td>10</td>
</tr>
<tr>
<td>Skewfix</td>
<td>Vertical MOVs</td>
<td>Skew-quad fields / vertical BPM offsets</td>
<td>9</td>
</tr>
<tr>
<td>Wirefix</td>
<td>Harmonic modulations of gradients with 2x betatron osc. frequency</td>
<td>Remaining lattice imperfections</td>
<td>11</td>
</tr>
</tbody>
</table>

Fig. 3: Dispersion of the electron beam in the (a) North Arc and (b) South Arc, measured March 10, 1989.

3. The “blow-up” factor of the betatron oscillations sent from the Arc entrance is less than 1.2 (ideally 1.0).
4. The detC parameter, characterizing the magnitude or remnant x-y coupling, is measured to be 0.006 at the exit of the North Arc (electron side, see Fig. 4), 0.13 for the South Arc (positron side). The detC, ideally, should be zero at the Arc exit.
5. With beam steering/energy feedback systems operating at the Arc entrance, the orbit (beam centroid) reproduces within 100 μm over weeks.

6. REMAINING ISSUES

One outstanding issue in the physics runs at the SLC is beam-related backgrounds in the detector. All of the evidence indicates that the beam transfer across the Arcs is very stable once a configuration is set up. However, the delicate interplay of beam collimators in the Arcs and FFs is quickly broken as the incoming beam condition changes.

As noted in the previous section the Arcs have been “tuned” to have a small net detC (i.e., very small remaining x-y coupling). However, this does not mean that the total “phase length” of the Arcs agrees exactly with the design. Therefore, frequently wirefix must be applied to introduce extra x-y coupling or to modify the beam transfer, so that the beam at the Arc exit is nearly matched to the FF. Using wirefix in this way is very practical and a rather quick solution to the problem at this moment of initial physics runs. However, a complete tune-up of the whole Arcs is being prepared with all the developed “fix” techniques to bring the system even closer to the ideal design. We hope that it will make the detector background less sensitive to the changes in the incoming beam conditions.

7. CONCLUSIONS

In the operation of the SLC Arcs we are equipped with powerful tools to (i) correct systematic gradient errors due mainly to horizontal placement errors (phasefix), (ii) correct systematic skew-field errors due mainly to vertical placement errors (skewfix), and (iii) can semi-empirically modify the effective beta functions at the Arc exit (wirefix). The Arcs are able to interface between the SLC linac and the SLC FF in a well-controlled fashion, so that electron and positron beams are delivered with sufficiently high quality for the first-round SLC runs.

REFERENCES

7. D. Burke et al., “Beam Collimation and Detector Backgrounds at e⁺e⁻ Colliders,” these proceedings.