SLAC–PUB–6209
May 1993
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Beam Based Alignment of the SLC Final Focus Sextupoles*

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ABSTRACT

The strong demagnification inherent in final focus systems requires local cancellation of the resulting chromaticity. Strong sextupole pairs separated by a $-I$ transform are positioned $\pi/2$ in betatron phase away from the Interaction Point (IP) in order to cancel chromatic aberrations primarily due to the final quadrupoles. Sextupole alignment is critical in order to provide orthogonal tuning of the chromaticity and, in the case of the SLC, to limit the third and higher order optical aberrations generated from misaligned and 'nested' horizontal and vertical sextupole pairs. Reported here is a novel technique for aligning the beam centroid to the sextupole centers, which uses measurements of *the* critically dependent parameter — the beam size at the IP. Results for the SLC final focus sextupoles are presented, where a resolution of <50 μm is achieved.

I. MOTIVATION

The motivation for achieving good static [1] sextupole alignment is actually two-fold in the SLC final focus. Tuning time is minimized by orthogonalizing chromaticity control with respect to IP beam waist adjustments ($\beta^{*\prime}$), dispersion control, and coupling correction. Furthermore, due to space requirements, the SLC final focus chromatic correction sections employ 'nested' horizontal and vertical sextupole pairs — four per final focus [2]. The linear optics between the two sextupole pairs are designed to provide a $-I$ transform to cancel geometric and chromatic dispersion aberrations. Misaligned sextupoles within the nested system generate skew and normal quadrupole fields which distort the $-I$ transform and so generate higher order optical aberrations which are not all correctable. Therefore, it is critical to achieve static alignment of these sextupoles to within ~200 μm for present SLC beam parameters.

II. THE ALIGNMENT METHOD

The sextupole pairs are placed $\pi/2$ in phase from the IP at points of large horizontal dispersion. Therefore, a horizontal sextupole offset will introduce a normal quadrupole field and generate horizontal IP dispersion and both horizontal and vertical waist shifts. A vertical offset will introduce a skew quadrupole field and generate vertical IP dispersion and coupling. The SLC final focus design provides orthogonal correction for each of these effects. By measuring the amount of IP waist, dispersion, and coupling change as a function of each sextupole strength, the horizontal and vertical sextupole offsets with respect to the final focus orbit are calculated. Alignment correction is implemented by closed orbit bumps with horizontal and vertical dipole corrector magnets within the final focus. A desirable quality of the technique is that the measurement tolerances are consistent with the alignment goals — if there are no measurable waist, dispersion, or coupling changes in the IP beam given significant sextupole strength changes, then the necessary alignment is achieved.

For SLC, there are just two power supplies for the four sextupoles per final focus. The two X-sextupoles (horizontal chromaticity correction) are in series on one supply, while the Y-sextupoles are in series on a second supply. Fortunately, due to the $-I$ transform between pairs, this is ideal — the waist, dispersion, and coupling changes at the IP can be independently separated into symmetric and anti-symmetric components of sextupole pair misalignment in X and Y. Figure 1 illustrates the eight different observable misalignment components. The individual sextupole misalignments are simply linear combinations of these eight components.

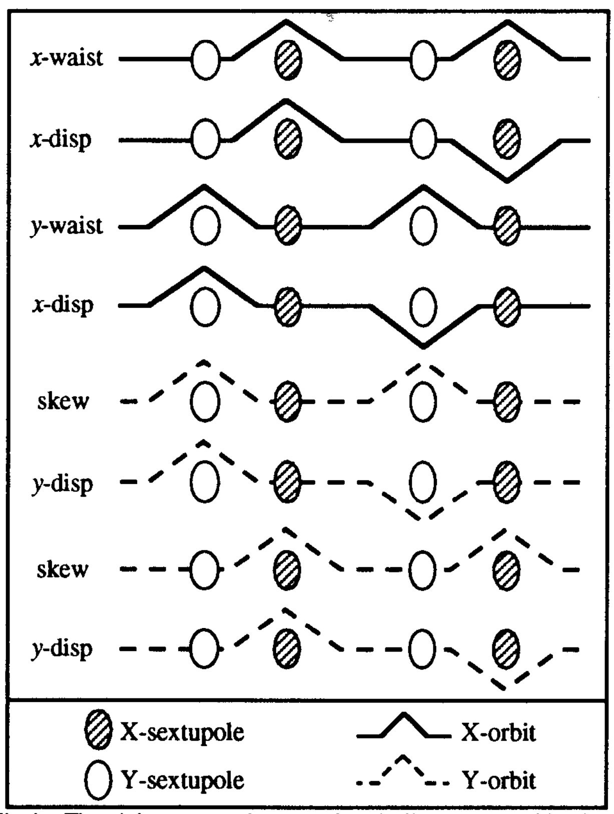

Fig 1. The eight measured sextupole misalignment combinations (4 per plane) and the dominant generated optical effect observed at the IP (waist shift, dispersion, and coupling or 'skew').

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

Presented at the Particle Accelerator Conference (PAC '93), Washington,DC, May 17-20, 1993

In order to illustrate the connection between misalignment components and generated optical effects suppose the sextupole is misaligned (x_0, y_0) with respect to the beam centroid. The sextupole kick angles, ($\Delta x'$, $\Delta y'$), of a particle with centroid position deviation ($x + \eta\delta$, y) in one sextupole of strength Δk then become

$$\Delta x'(x,y,\eta,\delta,x_0,y_0) = \frac{1}{2!}\Delta k\{(x+x_0+\eta\delta)^2 - (y+y_0)^2\} ,$$

$$\Delta y'(x,y,\eta,\delta,x_0,y_0) = \Delta k(x+x_0+\eta\delta)(y+y_0) . \quad (1)$$

Here δ is the fractional energy deviation ($=\delta E/E_0$) and η is the nominal horizontal dispersion at each sextupole per pair. Note, the final focus dispersion must first be corrected to fairly loose tolerances before the alignment procedure begins.

Each optical effect is labeled below in (2) and (3) after summing the two kicks due to misalignments of one sextupole pair and using the $-I$ transform between sextupoles. These kicks become positions at the IP through the R_{12} and R_{34} transfer matrix elements from relevant sextupole to IP.

$$\begin{aligned}
&\Delta x_1'(x,y,\eta,\delta,x_{01},y_{01}) - \Delta x_2'(-x,-y,\eta,\delta,x_{02},y_{02}) = && (2)\\
&2\Delta k x\eta\delta + && (x\text{-chromaticity})\\
&\Delta k x(x_{01}+x_{02}) + && (x\text{-waist})\\
&\Delta k\eta\delta(x_{01}-x_{02}) - && (x\text{-dispersion})\\
&\Delta k y(y_{01}+y_{02}) + && (\text{skew})\\
&\Delta k[(x_{01}^2-x_{02}^2)-(y_{01}^2-y_{02}^2)] && (x\text{-steering})
\end{aligned}$$

$$\begin{aligned}
&\Delta y_1'(x,y,\eta,\delta,x_{01},y_{01}) - \Delta y_2'(-x,-y,\eta,\delta,x_{02},y_{02}) = && (3)\\
&2\Delta k y\eta\delta + && (y\text{-chromaticity})\\
&\Delta k y(x_{01}+x_{02}) + && (y\text{-waist})\\
&\Delta k\eta\delta(y_{01}-y_{02}) + && (y\text{-dispersion})\\
&\Delta k x(y_{01}+y_{02}) + && (\text{skew})\\
&\Delta k(x_{01}y_{01}-x_{02}y_{02}) && (y\text{-steering})
\end{aligned}$$

With measurements of waist, dispersion, and skew changes at the IP as a function of sextupole pair strength changes, the symmetric, ($x_{01}+x_{02}$) and ($y_{01}+y_{02}$), and the asymmetric, ($x_{01}-x_{02}$) and ($y_{01}-y_{02}$), misalignment components are calculated per pair. For example, the horizontal symmetric misalignment of the X-sextupole pair is calculated by measuring the x-waist shift, Δw_x, per strength change, Δk, using the large R_{12} (3.3 m) from these sextupoles to IP.

$$\frac{1}{2}(x_{01}+x_{02}) = \frac{\Delta w_x}{2R_{12}^2\Delta k} \quad (4)$$

Figure 2 shows two 'waist-scans' done at different X-sextupole strength settings. The waist positions have shifted with respect to each other by Δw_x = 1.49 ± 0.09 cm for a sextupole strength change of Δk = 1.97 m^{-2} and indicate the symmetric horizontal misalignment is 354 ± 21 μm.

III. ALIGNMENT CORRECTION

After measurement of a specific misalignment component, an orbit bump is introduced with dipole corrector magnets which removes only that component. Figure 3 shows a large horizontal symmetric bump introduced at the Y-sextupoles to remove the y-waist dependence on Y-sextupole strength (shown is an extreme case of 1 mm to test bump closure).

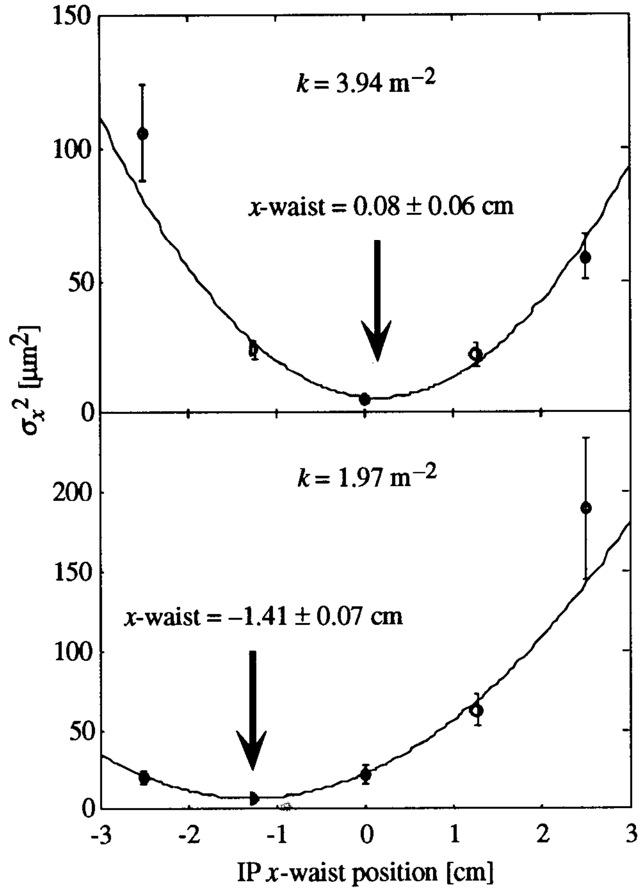

Fig 2. Two x-waist scans (IP beam size vs. waist position) done at different X-sextupole strengths, k, reveal a horizontal symmetric component of sextupole misalignment of 354 ± 21 μm.

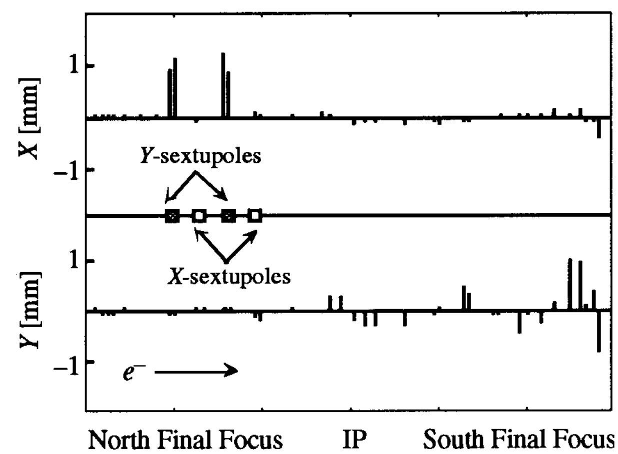

Fig 3. A horizontal symmetric e^- orbit bump introduced with dipole correctors to remove y-waist dependence on Y-sextupole strength (shown is an extreme case of 1 mm to test bump closure).

There are sufficient dipole correctors in the final focus to orthogonally correct all eight misalignment components per side (North e^- and South e^+). A second iteration is always performed to verify the sign and magnitude of correction. With large corrections (>400 μm), a second smaller correction is usually necessary to align to near measurement precision.

With the sextupoles detuned, uncorrected chromaticity causes the minima of these scans to increase. A practical approach is to run the two scans on either side of the nominal sextupole setting. This optimizes the waist measurement precision by reducing the chromatic increase.

To further optimize measurement precision, the IP beam size measurements are made at low beam current (0.5×10^{10}) with the existing 4 µm diameter Carbon filament wires near the IP [3]. The measurement is corrected for the large wire diameter and clean, reproducible results for the single beam of interest have been achieved down to 1.3 µm beam sizes [4].

When the alignment is complete and all corrections have been verified, two linear combinations of the two sextupole pair strengths are scanned to minimize the IP beam size per plane. The linear combinations are intended to orthogonally control horizontal and vertical IP chromaticity [5]. With the sextupoles aligned, these scans will now reliably minimize chromaticity and achieve the optimal IP beam sizes. Figure 4 shows a vertical chromaticity scan done after alignment which achieves a 1.55 µm vertical IP e^- beam size.

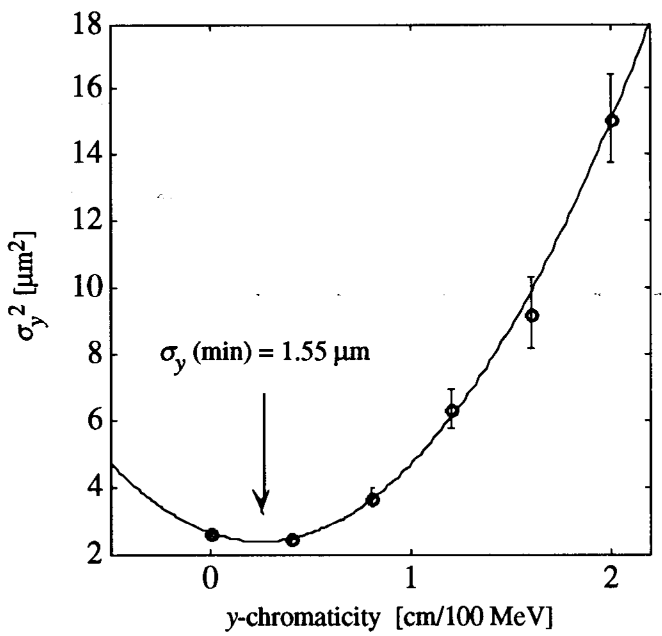

Fig 4. A vertical IP chromaticity scan after alignment which now truly minimizes chromaticity. The *y*-chromaticity control is a linear combination of sextupole pairs calibrated in centimeters of IP waist shift per 100 MeV energy deviation. A minimum spot of 1.55 µm is achieved.

Care must be taken during normal operations to maintain each final focus orbit over the duration of the run. Occasionally orbit distortions appear which may be traced to beam position monitor (BPM) offset drifts or actual trajectory changes within the final focus. These changes must be verified and, if necessary, corrected with some subset of the alignment techniques described above. No steering is done within the final focus chromatic correction sections without verification of the sextupole alignment.

IV. CONCLUSIONS

This sextupole alignment technique has been used successfully before each of the 1992 and 1993 SLC/SLD luminosity runs during initial machine setup. Immediate impact was seen on IP beam sizes obtainable and overall final focus tuning time. The dramatic increase in SLC luminosity over the last two years owes, in part, to careful initial final focus sextupole alignment.

V. ACKNOWLEDGMENTS

The authors are grateful to the SLC operations staff for the many hours of machine stability necessary to complete the alignment.

VI. REFERENCES

[1] In this case 'static' refers to a time scale of many hours. Small diurnal variations are compensated with normal daily tuning.

[2] The original SLC final focus design used eight sextupoles per side. Subsequent investigations showed that only four were useful. Presently only four are powered which improves alignment tolerances.

[3] C. Field, "Problems in Measuring Micron Size Beams", *Proc. Particle Accelerator Conference*, Chicago, Illinois (March 1989).

[4] IP wire measurements are made in 'round-beam' mode where the horizontal and vertical emittances are nearly equal. In 'flat-beam' mode — decoupling the damping ring tunes — the optimized vertical IP beam size is ~0.8 µm.

[5] N. Toge, *et al.*, "Chromaticity Corrections in the SLC Final Focus System", *Proc. Particle Accelerator Conference*, San Francisco, California (May 1991).