CORRECTION OF HORIZONTAL-VERTICAL COUPLING IN THE SSC

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Abstract

Coupling between the horizontal and vertical betatron motion in the SSC is produced by skew quadrupole errors in the dipole magnets, angular alignment errors in the quadrupoles, and vertical closed-orbit errors in the sextupoles. The anticipated random errors in the arcs alone will produce a coupling coefficient of about 0.017 in the current lattice. The largest source of coupling for collision optics is expected to be the quadrupole triplets adjacent to the low-beta interaction points, each pair of which, if uncorrected can contribute about 0.05 to the coupling coefficient. A correction scheme using skew quadruples at favorable positions in the interaction straight sections has been devised and tested. An interactive, graphical simulation was performed using this corrector configuration. In the simulation each skew quadrupole family was set to the value which minimized the separation between the two tunes, cycling between families until the machine was sufficiently decoupled ($|C| < 0.001$).

Introduction

Coupling between horizontal and vertical betatron oscillations in the SSC can cause serious operational problems. Because of coupling the betatron tunes can become difficult (or impossible) to measure and hard to interpret. Collective oscillations become difficult to correct and thus can lead to emittance growth through filamentation. Beam diagnosis and correction are severely hampered. For good operation it is desirable to keep the coupling coefficient (C) below 0.005. The coupling coefficient is taken as half the minimum separation that can be achieved between the two eigenfrequencies of the beam (normally the horizontal and vertical betatron tunes).

Sources of Coupling

Coupling between horizontal and vertical betatron motions is caused primarily by skew quadrupole components. There are three principal sources:

(1) angular misalignment of the quadrupole magnets,

(2) skew quadrupole components in the dipole magnets, and

(3) skew quadrupole components due to feed down in various sextupole elements from vertical closed-orbit excursions.

In this paper we consider the coupling produced by the random skew quadrupole components. That is, the systematic skew quadrupole components are assumed to be either negligibly small or adequately corrected.

We will consider the coupling contributions due to the random skew components in the arcs and in the straight sections separately. These contributions will be added in quadrature to find the ring total. We will use the coupling formulas developed in the SSC Conceptual Design Report.[1]

Coupling Produced in the Arcs

The two collider arcs consist of 286 identical FODO cells, each cell containing 12 dipoles, two quadrupoles, and two chromaticity sextupoles. The arcs cover about 78% of the ring circumference.

The rms coupling coefficient produced in the arcs by the random angular misalignment σ_ϕ of the quadrupoles in the arcs is:

$$|C_q| = N^{1/2} (\beta_x\beta_y)^{1/2}_{avg}\, 2\sqrt{2}\, \sigma_\phi/(4\pi f) \qquad (1)$$

where N is the number of cells, $(\beta_x\beta_y)_{avg}$ is the average of the product of the two beta functions at the quadrupoles, and f is the quadrupole focal length.

The rms coupling coefficient produced by the skew quadrupole component in the dipoles of the arcs is

$$|C_d| = N^{1/2}\, n^{1/2} (\beta_x\beta_y)^{1/2}_{avg}\, a_1\, \theta_1/(4\pi) \qquad (2)$$

where n is the number of dipoles per cell, a_1 is the rms variation of the skew quadrupole coefficient, and θ_1 is the bend angle per dipole.

The rms coupling coefficient produced by the interaction of a random vertical closed orbit in the chromaticity sextupoles in the arcs is:

$$|C_s| = N^{1/2} \sqrt{2}\, \sigma_y\, r/(4\pi f\, \eta_{avg}) \qquad (3)$$

where σ_y is the rms amplitude of the vertical closed orbit, r is the ratio of the total chromaticity to that produced in the arcs, and η_{avg} is the average value of the dispersion function in the arcs.

Evaluating (1), (2), and (3) for $\sigma_\phi = 0.5 \times 10^{-3}$ radian, $a_1 = 1.2 \times 10^{-2}\ m^{-1}$, $\theta_1 = 1.64 \times 10^{-3}$ radian, $\sigma_n = 1$ mm, r = 2, $\eta_{avg} = 2.26$ meter, and $(\beta_x\beta_y)^{1/2}_{avg} = 169$ meter and combining the three contributions in quadrature gives a arc coupling coefficient of

$$|C_{arc}| = 0.017$$

most of which is due to the skew quadrupole component in the dipoles.

Coupling Produced in the Straight Sections

The collider ring contains 8 straight sections, of which 2 are "low-beta" interaction regions, 2 are "medium-beta" interaction regions, and the other 4 are utility straight sections, which are provided for injection, abort, and RF functions, and for future expansion. Each "straight section" includes 1.5 normal FODO cells (like those in the arcs) plus 4 special dispersion-suppressor FODO cells in addition to the special quadrupoles that produce the interaction-region optics. Along each beam line in each of the low-beta and the medium-beta straight sections there are 30 such special quadrupoles.

The main concern with respect to coupling effects are the very strong triplet quadrupole arrays on each side of each interaction point. Not only are these triplet quads unusually strong, but also the beta functions at these points are unusually high, so that they are especially potent sources of coupling.

The doublet quads in the utility straight sections are not as worrisome, since their strengths and beta-function values are relatively small and there are only 8 such quadrupoles in each beam line in each utility straight section.

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Equations (1) and (2) are easily modified to apply to the irregular structures of the straight sections. Using the same σ_ϕ for the IR quads and the same a_1 for the dispersion suppressor dipoles as used for the arcs, and the individual IR quadrupole strengths and the corresponding beta-function values, we calculate the following contributions to the coupling coefficient:

from 2 low-beta straight sections

$$|C_{lb}| = 0.071$$

from 2 medium-beta straight sections

$$|C_{mb}| = 0.026$$

from 4 utility straight sections

$$|C_u| = 0.009$$

Combining these contributions to the coupling coefficient from the various random skew-quadrupole sources in the straight sections in quadrature with those from the arcs gives a total-ring coupling coefficient of 0.078. If the same estimate is made excluding all of the inner-triplet quadrupoles (at the four interaction points), the estimated total-ring coupling coefficient is only 0.022. Thus one is motivated to consider whether strong local contributions to the coupling coefficient can be properly diagnosed and locally corrected. Ordinarily it is only the global (ring-wide total) coupling coefficient that is measured.

Correction

The coupling produced in the dynamics of a beam particle during one turn of the storage ring can be eliminated by one skew quadrupole if the relative betatron phase ($\varphi_x - \varphi_y$) between the horizontal and vertical motion is appropriate. To cover all possible phases a pair of skew-quadrupole correctors at positions separated in relative phase by 90° is adequate. Having several such pairs of skew-quadrupole correctors is desirable if a large correction is required.

In the SSC the only locations where adequate variation of relative phase is available is in the special-optics regions of the straight sections. In the arc sections suitable skew-quadrupole corrector locations are not available because the relative phase ($\varphi_x - \varphi_y$) varies by only ±20° for the nominal betatron tune. ($\nu_x = 96.285$, $\nu_y = 96.265$). Figure 1 shows that in the low-beta and medium-beta straight sections there are locations for pairs of skew-quadrupole correctors that differ by up to 130° in relative phase, and in both sets of optics—i.e., in both injection optics and in collision optics. In the utility straight section the available difference in relative phase is only about 65°, but even that amount can be used effectively.

The positions for the skew quadrupole correctors that the present study suggests are tabulated below and indicated in Figure 1.

Table I. Suggested positions for pairs of skew quadrupole correctors.

Straight Section	Skew Quad Family	Position*	Injection Optics β_x	β_y	$\phi_x - \phi_y$*	Collision Optics† β_x	β_y	$\phi_x - \phi_y$*
Low Beta	SQA	461 m	69 m	400 m	~0°	69 m	380 m	~5°
	SQB	986	380	160	135°	6,000	2,400	125°
Medium Beta	SQA	461	68	400	~0°	69	385	~5
	SQB	888	280	120	105°	1,500	815	110°
Utility	SQA	502	184	94	10°		(same)	
	SQB	768	845	480	−50°		(same)	

*Position and relative phase are taken as zero at the beginning of each straight-section insertion. The center of each straight section is at 1085 meters.

†The optics of the utility straight section is unchanged when the ring is tuned between "injection" and "collision" optics.

Testing of the Coupling-Correction System

The coupling-correction scheme proposed in this report was tested by simulation.[2] In the simulation all of the quadrupoles in the SSC ring were rotated with a random rms variation $\sigma_\phi = 0.5$ mrad and translated with random rms variations of $\sigma_x = \sigma_y = 0.5$ mm. All dipoles were rotated with $\sigma_\phi = 1.0$ mrad, translated with $\sigma_x = \sigma_y = 0.5$ mm, and assigned random multipole errors $\sigma(a_0) = 5.9$ "units"*, $\sigma(b_0) = 3.0$, $\sigma(a_1) = 0.72$, $\sigma(b_1) = 0.72$, $\sigma(a_2) = 0.64$, and $\sigma(b_2) = 0.40$.

The simulation procedure was interactive and modeled procedures used in existing accelerators. The closed orbit was corrected using an algorithm based on overlapping localized bumps. The resulting rms orbit displacements at the simulated beam position monitors varied between 0.2 and 0.3 mm in each transverse plane.

The skew-quad corrector layout that was tested is indicated in Figure 1. It is not the layout proposed in this paper but it serves to test the method.

The decoupling technique proceeds as follows. An interactive graphics program running on a SUN Workstation, whose underlying physics model is based on the TEAPOT[3] particle-tracking program, plots the fractional parts of the betatron tunes (obtained using a coupled Twiss analysis)[4] as a function of either one normal trim quadrupole circuit or one of the two skew quadrupole corrector circuits. In a real accelerator, a spectrum analyzer is used to obtain these tunes. Additional points on the plot are obtained via mouse and menu. Figure 2 illustrates the method. When the plot clearly shows a minimum in the separation between the two betatron tunes, the value at which that minimum occurs is selected using the mouse, and the program sets the skew quadrupole strength to the chosen value. The other skew quadrupole circuit can then

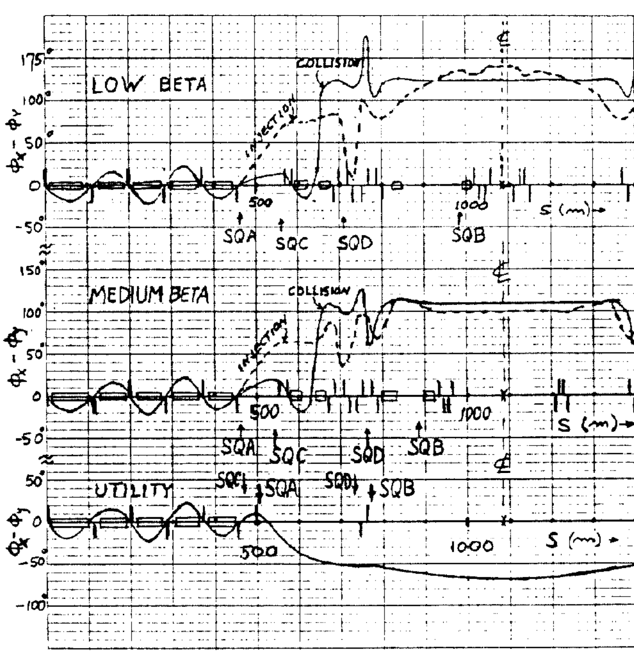

Fig. 1 Variation of the relative betatron phase in the three types of straight sections for collision and for injection optics. SQA and SQB indicate the positions of the two families of skew quadrupole correctors proposed in this report. SQC and SQD indicate the positions tested in the simulation.

* One "unit" of multipole strength is 10^{-4} of the dipole strength at 1 cm. a_n is the skew coefficient of the 2(n+1) multipole and b_n the normal coefficient.

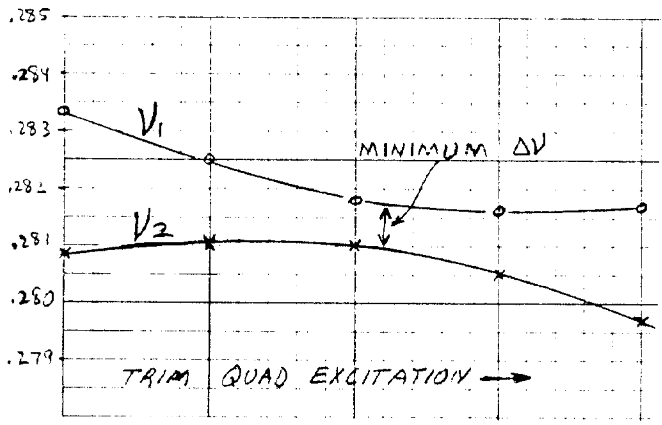

Fig. 2 Finding the minimum separation of the two betatron frequencies.

be selected. In this fashion the minimum tune separation can be made progressively smaller, until the user is satisfied. At anytime the coupling coefficient can be computed.

Results

The corrector locations used in this test were found to be satisfactory for the injection optics. This result is consistent with the relative phase plots in Figure 1, which shows that there is adequate although not optimum phase difference between the two skew quadrupole families SQC and SQD in injection optics.

The correction method converged rapidly. In collisions optics only one iteration was adequate to achieve coupling coefficients less than 0.001. The results for 4 random seeds were as follows:

Table 2. Initial and final coupling coefficients and the required skew sextupole corrector strengths for 4 random seeds.

Seed	$2\,|C|_{initial}$	$2\,|C|_{final}$	SQC	SQD
1	0.050	0.00005	$0.14 \times 10^{-3}\ m^{-1}$	$0.70 \times 10^{-4}\ m^{-1}$
2	0.013	0.00048	-0.87×10^{-5}	-0.36×10^{-4}
3	0.015	0.00044	-0.19×10^{-4}	-0.44×10^{-4}
4	0.017	0.00077	-0.30×10^{-4}	0.45×10^{-4}

The required septupole strengths are relatively weak. The largest strength listed is only 0.56×10^{-2} of the normal cell quadrupole strength ($0.0125\ m^{-1}$).

References

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