COMPENSATION OF MAGNETIC IMPERFECTIONS IN THE SSC.

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Introduction.

We discuss the compensation of nonlinear multipole errors in the magnets of the SSC. The results described here have mainly been obtained using TEAPOT.[1] An SSC modeling program was used for some cases, to investigate the operational feasibility correction of the schemes.[2] Far more details are contained in reference 3. Because the cost of the SSC is dominated by the main arcs, and because the optical defects of those arcs are dominated by field errors in the superconducting dipoles, this study focuses on compensating for those field errors.

Degradation due to nonlinear field errors can be quantified by tune shifts and by "smear" (the fractional r.m.s. deviation of the Courant-Snyder invariant.) In analyzing the SSC the following approximate "principles" have usually been found to be approximately valid: (i) systematic multipole errors cause tune shifts and not smear, and (ii) random multipole errors cause smear and not tune shifts. Our studies have eroded this separation a bit, since random orbit errors, in combination with systematic multipole errors are found to contribute significantly to smear. For that reason we cannot neglect closed orbit errors, which conspire with these errors to cause coupling and smear.

Ideally the dipole fields would be perfect, and next best would be compensation coils precisely superimposed on the errors they are correcting. Both of these are unrealistic, and the compensation elements will always be somewhat remote from the errors. We will, however, use the term "remote" in a more exaggerated sense to imply correction elements which are displaced by at least one, and typically many, cells from the error they are compensating. "Local" will mean "in the same half-cell."

Correction Schemes Considered.

The correction issue impacting most strongly on the SSC plan is whether to use bore-tube correctors or lumped correctors. The important error effects, such as deflection and displacement errors, and chromaticity, are described by formulas consisting of sums of integrals over half-cells of length ℓ of the form

$$\int_{-\ell/2}^{\ell/2} [b_2^{(E)} + b_2^{(C)}(s)] s^p ds$$

where p is a small integer, $b_2^{(E)}$ is the dipole multipole error (assumed to be independent of distance s along the beam line), and $b_2^{(C)}(s)$ is the correction multipole, lumped or distributed. A natural approach to compensation is to choose $b_2^{(C)}(s)$ to make these terms vanish for values of p not greater than some value p_{max}. As emphasized by Neuffer[4] these conditions are equivalent to numerical quadrature formulas. The two most promising candidate formulas are Simpson's rule and Gaussian quadrature.[5]

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The various correction coil configuration possibilities were distilled down to four schemes which had performed best in early screening assuming no closed orbit errors. They were assigned acronyms

(1) BCDR, having boretube coils for b_2, b_3, and b_4.

(2) BFUL5, having boretube coils for b_2, but remote, lumped coils for b_3 and b_4, in every fifth cell.

(3) SNEU, having lumped correctors based on Simpson's rule.

(4) GAUI, having lumped correctors based on a Gaussian integration rule.

SNEU is now indicated pictorially, labelling correctors F, D, or C, depending on whether they are beside F or D quads, or in the center:

$$\Big|\Big) F_+[\ ][\ ][\ ]C[\ ][\ ][\ ]D_- \Big)\Big(D_+[\ ][\ ][\ ]C[\ ][\ ][\ ]F_- \Big(\Big|.$$

where individual dipole magnets are represented by the symbol [ ]. It has usually been assumed, and has not been contradicted during this study, that the lumps on either side of a lattice quad can, with impunity, be combined into a single lump. The correctors, D_- and D_+, would be lumped together on one or the other side of the D-quad, and the F-correctors would be similarly lumped. The result is shown:

$$\Big|\Big) F[\ ][\ ][\ ]C[\ ][\ ][\ ] \Big)\Big(D[\ ][\ ][\ ]C[\ ][\ ][\ ] \Big(\Big|.$$

The Gaussian quadrature scheme, GAUI, is illustrated next, with lumped correctors indicated by G:

$$\Big|\Big) [\ ]G[\ ][\ ][\ ]G[\ ] \Big)\Big([\ ]G[\ ][\ ][\ ]G[\ ] \Big(\Big|$$

The Simpson scheme is less symmetric and the coefficient of its error term is worse by a factor of 1.5 than for the Gaussian scheme in spite of having 3 rather than 2 lumps, but this difference is minimal and, as just mentioned, two of the correctors can presumably be combined. Also GAUI has no end effects, but it requires the number of magnet units per half-cell to be a multiple of 5.

Analysis Procedures.

Three forms of theoretical (numerical) analysis are employed, each starting with a prescription for setting the correctors, continuing by tracking extreme particles for some hundreds of turns, using TEAPOT, and finishing by FFT extraction of the smear and tune for each particle. They are:

(I) Compensation of systematic magnet multipoles assuming no random magnet errors and no closed orbit errors.

(II) Compensation of random magnet errors in the presence of already corrected systematic errors but with no closed-orbit errors.

(*III*) Inclusion of random closed orbit errors and other errors.

Assumed Errors and Specification of Performance. The main systematic errors, at the time of injection, which is the most critical time, are $b_2 = -7.4, b_4 = 0.64$, and $b_6 = -0.13$, coming from persistent currents. These are in the usual units of parts per 10^4 at one centimeter. The main random errors have standard deviations given by $\sigma_{b2} = 2.0, \sigma_{a2} = 0.6, \sigma_{b3} = 0.3$, and $\sigma_{b4} = 0.7$.

A lattice consisting only of 320 simple 90° FODO cells, with parameters identical to those in the regular arcs of the SSC, is assumed. In all cases the tunes were adjusted to the values $Q_x = 81.285, Q_y = 82.265$.

For the SSC, performance specifications have been set for a "needed aperture" having transverse amplitudes up to 5mm, on-momentum, and up to 3mm, for fractional momentum deviation equal to 0.001. Within this aperture the maximum tune variation is to remain in the range ±0.005; the smear is to remain less than 10%.

To begin with the tunes were set to their nominal values and both chromaticities were adjusted to zero, using the sextupoles situated next to the main arc quadrupoles. After introducing the errors the compensators were set, using calculations based on the those errors (assumed to be perfectly known). An operational approach was then taken, of re-adjusting the chromaticities to zero, with the chromaticity sextupoles; this assumes that the chromaticity will be operationally measureable on the SSC, even during tune-up.

Results With No Closed Orbit Errors.

1. Tune Control. All four schemes meet the requirement of constancy of the tunes, at both small and large amplitude, both on and off-momentum.

2. Remote Compensation. For compensation of small multipole errors, remote compensation is potentially economical and satisfactory. The study was predicated on the hope that all of b_3, b_4, and b_6 could be compensated remotely, where remotely means every 10 or so cells. This was born out by the study; for subsequent studies a remote period of 5 was used.

3. Spool-Piece-Only Compensation. In the Tevatron all correction elements are located in "spool-pieces" that are situated immediately next to main arc quadrupoles. It is natural to contemplate a similar configuration for the SSC; it is more economical to include multipole correctors in those locations than in the cell interior. For that reason, considerable effort was expended in attempting to achieve satisfactory systematic compensation without the use of interior elements. Compensator settings were selected to make the "large-amplitude interpolated transfer map",[6] as generated by TEAPOT, deviate as little as possible from the small-amplitude map. Still, for the expected errors, the SSC specification could not be met by about a factor of four.

4. Operational Performance.

For some of our investigations we have intentionally restricted ourselves to parameter adjustment algorithms that employ only information which would reasonably be expected to be operationally available on the accelerator. Closed-orbit control, and chromaticity control have been modeled satisfactorily under many conditions.[2] The previously mentioned satisfactory small-amplitude behavior can be achieved empirically, using tune measurements on the circulating beam, without relying on the measured, or calculated, systematic field errors. We are not relying, however, on being able to compensate the large-amplitude behavior empirically.

5. Compensation of Random Multipoles. All four compensation schemes are sufficiently fine-grained to yield satisfactory improvement of the linear aperture by means of the "binning" compensation of random errors.[7] Sensitivity to errors which are partly random, partly systematic, has not been studied.

Sensitivity to Closed-Orbit Errors.

To this point in the study, the candidate lattices had satisfied the requirements of systematic compensation and of random compensation. In some ways performance of one or the other had been found to be measurably superior, but the differences are small, probably not great enough to stack up against qualitatively different considerations like cost and practicality. The more delicate issue of sensitivity to closed orbit errors, potentially gives gives a greater selectivity among the schemes.

The same four schemes studied previously were used to study sensitivity to orbit errors caused by quadrupole magnet misalignment, dipole magnet rotation and misalignment, and dipole magnet field errors. These studies were conducted with only systematic multipole errors, no random multipole errors. Results are shown in the table.

Smears and Tune Shifts with Random Orbit Errors and Systematic Dipole Errors

	amplitudes		tunes		smears(%)	
	x(mm)	y(mm)	Q_x	Q_y	S_x	S_y
BCDR	0.0	0.0	0.2852	0.2653	0.0	0.0
	3.0	3.0	0.2851	0.2653	1.0	1.5
	5.0	5.0	0.2851	0.2654	2.2	3.9
	6.0	6.0	0.2850	0.2655	2.9	5.4
BFUL5	0.0	0.0	0.2851	0.2655	0.0	0.0
	3.0	3.0	0.2848	0.2656	2.3	2.6
	5.0	5.0	0.2836	0.2661	6.5*	6.5*
	6.0	6.0	0.2835	0.2675	9.9	9.4
SNEU	0.0	0.0	0.2850	0.2650	0.0	0.0
	3.0	3.0	0.2851	0.2655	1.2	0.9
	5.0	5.0	0.2852	0.2656	2.8	2.0
	6.0	6.0	0.2652	0.2657	4.0	2.9
GAUI	0.0	0.0	0.2851	0.2653	0.0	0.0
	3.0	3.0	0.2850	0.2652	0.9	1.1
	5.0	5.0	0.2847	0.2646	2.0	2.5
	6.0	6.0	0.2841	0.2641	2.8	3.5

BCDR, BFUL5, SNEU and GAUI were all prepared in the following way: systematic multipole errors were added and the correctors were set to compensate them; the alignment and field errors mentioned above, with strengths adjusted to produce the desired residual closed orbit errors, were added and the orbit was corrected, leaving a ±1mm r.m.s. orbit; the tunes and linear chromaticities were set; the resulting machines were tracked for 512 turns, with the smears and tunes shifts being measured for various amplitude particles, all on-momentum. To date, only one random seed has been studied. It is worth remembering, while looking at the tracking results, that the needed aperture of 5mm decreases by approximately 1.25mm when orbit errors are present in the machine being tracked. That is, part of the needed aperture is for orbit errors, so if they are included in the simulation, they can be subtracted from the needed aperture. Although the machines studied had only systematic multipole errors, non-zero smear was anticipated since the orbit errors cause randomness in the feed-down of the systematic multipoles: that has the same effect as random multipole errors. The smears and tune shifts are given in the table. The behavior of BFUL5 is the worst, but it still meets the CDR specification. Further investigation confirmed that its smear was dominated by feed-down from the remote correctors. This will be called the "worst thing found" as it is discussed further below.

Conclusions.

(1.) Either distributed or sufficiently fine-grained, lumped compensation can yield satisfactory results, as far as accelerator theory is concerned. One product of this investigation has been a set of comparably performing configurations, which represent the main options. Deciding among them depends on administrative weighting of various factors: manufacturing feasibility, desirability of separating functions, preserving flexibility, cost, operational ease, and so on.

(2.) Systematic multipole errors have a large effect upon global properties like chromaticity. It has been found, in the absence of other effects, that compensation has been straightforward, even using "remote" compensation schemes having correctors many half-cells away from the errors being compensated. It is found, however, that performance of such remote schemes is degraded by the simultaneous inclusion of other errors, notably closed-orbit errors.

(3.) Within the guidelines of the CDR, compensation of random errors has also been found to be satisfactory, with compensation of just b_2 reducing the "smear" to about 5% within the "needed aperture". Nothing in this study bears on the question of what constitutes a tolerable level of smear.

(4.) To the extent comparisons have been made, projections of the CDR have been largely born out. Examples are closed-orbit, tune, and chromaticity adjustment as anticipated there. In particular, the correction with b_2, b_3, and b_4 coils mounted on the bore-tube has permitted the compensation of both systematic and randoms as well as any other scheme studied. The remote, lumped elements present in that design have been used for successful remote compensation, but the same reservation made previously about remote compensation suggests replacing the remote elements of the CDR design. In principle, even random errors could be compensated to some degree by those remote correctors, but no practical way of doing this has been found (nor really looked for seriously).

(5.) The most critical issue identified in the study has been the conspiracy of different errors which complicates the task of compensation. This complication makes itself progressively more important as the simulation includes more effects. Most noticeable so far have been difficulty in decoupling, increases in smear, and deterioration of remote compensation schemes when closed-orbit errors are included realistically.

(6.) As well as projecting ultimate performance it is important to investigate the operational practicality of diagnostic and adjustment schemes. According to the simulation, compensation of small-amplitude behavior (mainly as a function of momentum) has been shown to be quite feasible, but large amplitude behavior has not yet been adequately investigated.

(7.) For this study the lattice parameters were mainly held frozen. There was no systematic investigation of what could be "bought" by more favorable choices of main parameters like bore size and injection energy. To some extent though, the degree of difficulty we found in our narrow investigations can be quantified to give our input to important issues such as that. Two possibilities that can be considered are doubling the injection energy, and increasing the dipole bore diameter, say from 4 cm. to 5 cm. Some projections as to the improvements which would result follow:

(*i*) Doubling the machine injection energy would reduce the systematic injection values of b_2 and b_4, the leading offenders, by factors of $3.0/7.4 = 0.40$ and $0.20/0.64 = 0.31$ respectively. The latter factor could be applied directly, as an improvement factor, to the "worst thing found" in this study, which was mentioned in item (4) above; since the closed-orbit errors would presumably be independent of injection energy, only the absolute error multipole value would enter into the calculation of the feed-down.

(*ii*) The small term b_4 was deemed more important than the large term b_2 in the previous point only because the large b_2 term was assumed to be already compensated. This would still be necessary after doubling the injection energy, though naturally it would be much less critical.

(*iii*) Similar statements about systematic errors could be made about increasing the bore diameter by 25%; the b_2 and b_4 ratios would be $4.7/7.4 = 0.63$ and $0.30/0.64 = 0.47$ respectively. The fact that a 25% increase in bore diameter yields more than a factor of two improvement in this particular aspect of transverse behavior can be ascribed to the unhappily slow convergence of the multipole series.

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