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SSC CLOSED-ORBIT CORRECTION

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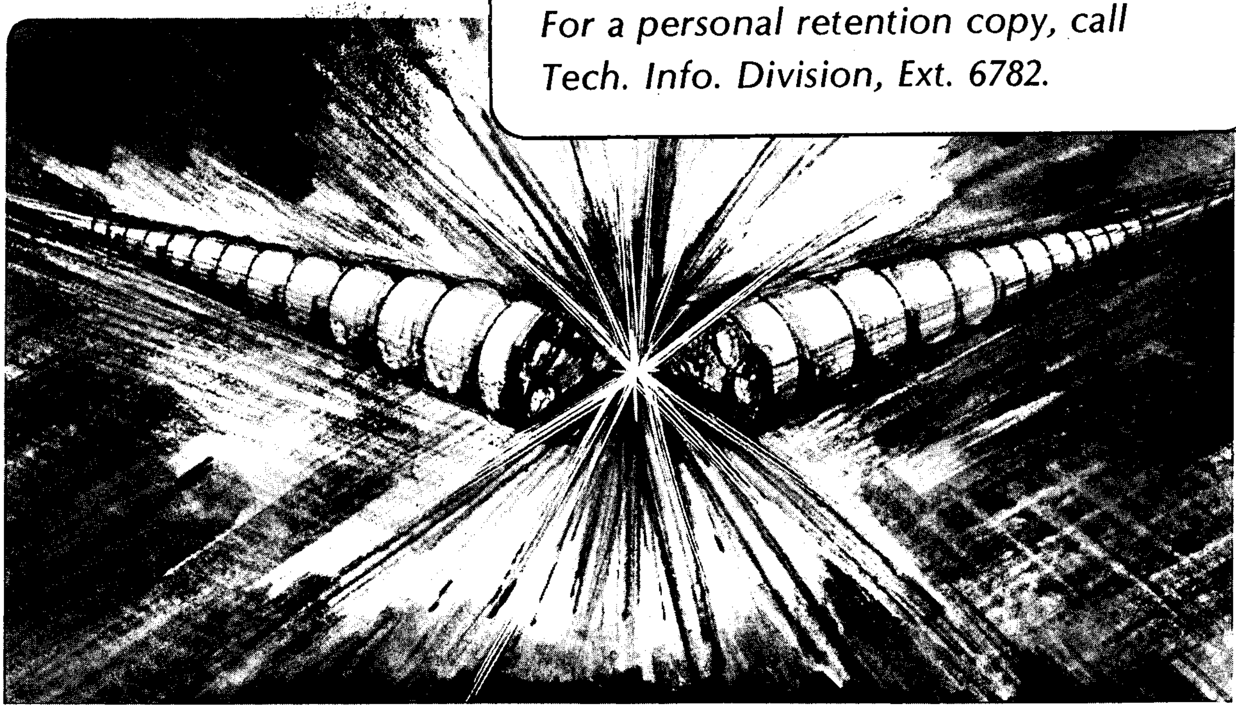

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I. Introduction

Because of its large size (~100 km circumference), survey, alignment, and closed-orbit correction of the SSC will be challenging tasks. For example, the fact that the accelerator will have as small a magnet aperture as practicable means that the closed-orbit corrections must be very precise. A preliminary estimate, however, suggested[1] that the closed-orbit errors may be quite large and difficult to correct properly. In this paper we will attempt to estimate the expected magnitude of closed-orbit errors in the SSC, and the corrector strengths required to compensate for them. A separate paper[2] will deal with the techniques and requirements for the initial SSC survey and alignment.

Formulae for closed-orbit deviations will be parametrized here in such a way that they can be applied easily to the various lattice examples that presently exist and to those that will undoubtedly be generated in the future. To give a feeling for the magnitude of the various terms, a few numerical examples based on the 6.5 T LBL lattice[3] will be presented. Scaling to other "personal favorites" should be straightforward.

Recent experience at Fermilab concerning the alignment and closed-orbit correction scheme in the Energy Saver/Doubler will be discussed as a guide to the practical aspects of what can be achieved at an operating superconducting accelerator.

II. Closed-Orbit Deviations

A. Basic Formulae

In the horizontal plane, the primary causes of closed-orbit deviations are: (a) random quadrupole misalignments; and (b) random errors in the dipole field. Deviations in the vertical plane are caused mainly by: (c) random quadrupole displacements; and (d) dipole "roll." King[4] has summarized formulae that can be used to estimate the maximum closed-orbit deviations from each of these effects (to 98% probability). They are:

(a), (c) Random Quadrupole Displacements

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} \simeq 1.2\, f(\nu) \left[\beta_{max}\bar{\beta}\right]^{1/2} M_Q^{1/2} (K\ell_Q)\, (\Delta Q)_{rms} \qquad (1)$$

where $\bar{\beta} = \frac{1}{2}(\beta_{max}+\beta_{min})$ [m]

K = quadrupole strength = $\frac{\text{gradient}}{B\rho}$ [m^{-2}]

ℓ_Q = quadrupole length [m]

M_Q = total no. of quadrupoles

$(\Delta Q)_{rms}$ = rms deviation of quadrupoles [m]

ν = betatron tune of machine

and $f(\nu) = \left[\frac{1 + |\sin \pi\nu|/3}{|\sin \pi\nu|}\right]$

(b) Random Dipole Field Errors

$$\hat{x}_{\Delta B} \simeq 2.4\,\pi\, f(\nu) \left[\beta_{max}\bar{\beta}\right]^{1/2} \left[M_B\right]^{-1/2} \left(\frac{\Delta B}{B}\right)_{rms} \qquad (2)$$

where M_B = total no. of dipoles

$\left(\frac{\Delta B}{B}\right)_{rms}$ = rms dipole field error

and the other symbols are defined in the previous equation.

(d) Random Dipole Roll

$$\hat{y}_{\Delta\phi} \simeq 2.4\,\pi\, f(\nu) \left[\beta_{max}\bar{\beta}\right]^{1/2} \left[M_B\right]^{-1/2} (\Delta\phi)_{rms} \qquad (3)$$

where $(\Delta\phi)_{rms}$ = rms roll angle of dipoles.

B. Parametrized Formulae

To assist in applying the above formulae to various SSC lattices, and to elucidate the manner by which the effects scale for different choices of lattice parameters, it is convenient to parametrize the expressions in terms of the cell length, L_{cell}, the phase advance per cell, μ, and the tune ν.

For a regular FODO cell of phase advance μ we have:

$$K\ell_Q = \frac{1}{F} = \frac{4 \sin(\mu/2)}{L_{cell}} \qquad (4)$$

$$\beta_{max} = \frac{L_{cell}}{\sin \mu} (1 + \sin(\mu/2)) \qquad (5)$$

and

$$\beta_{min} = \frac{L_{cell}}{\sin \mu} (1 - \sin(\mu/2)). \qquad (6)$$

Then

$$\bar{\beta} = \tfrac{1}{2}(\beta_{max}+\beta_{min}) = \frac{L_{cell}}{\sin \mu} \qquad (7)$$

and

$$\left[\beta_{max}\bar{\beta}\right]^{1/2} = \frac{L_{cell}}{\sin \mu}\left[1+\sin(\mu/2)\right]^{1/2} \qquad (8)$$

In addition, we can estimate the number of regular cells by

$$N_{cell} \simeq \frac{2\pi\nu}{\mu}, \qquad (9)$$

whence

$$M_Q = 2N_{cell} = \frac{4\pi\nu}{\mu} \qquad (10)$$

and

$$M_B = mN_{cell} = \frac{2\pi m\nu}{\mu}, \qquad (11)$$

where m is the number of dipoles per cell in a particular lattice design.

With these substitutions, equations (1) - (3) can be rewritten as:

(a), (c) Random Quadrupole Displacements

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} = 17.0\, f(\nu)\frac{\sin(\mu/2)}{\sin(\mu)} \left[1+\sin(\mu/2)\right]^{1/2} \cdot\left(\frac{\nu}{\mu}\right)^{1/2}(\Delta Q)_{rms} \qquad (1')$$

(b) Random Dipole Field Errors

$$\hat{x}_{\Delta B} = 3.0\, f(\nu)\frac{L_{cell}}{\sin \mu} \left[1+\sin(\mu/2)\right]^{1/2} \left(\frac{\mu}{m\nu}\right)^{1/2} \left(\frac{\Delta B}{B}\right)_{rms} \qquad (2')$$

(c) Random Dipole Roll

$$\hat{y}_{\Delta\phi} = 3.0\, f(\nu)\frac{L_{cell}}{\sin \mu} \left[1+\sin(\mu/2)\right]^{1/2} \left(\frac{\mu}{m\nu}\right)^{1/2} (\Delta\phi)_{rms} \qquad (3')$$

We note that $f(\nu)$ depends only on the fractional part of the tune and that it is symmetric about its minimum value at a fractional tune of 0.5. Typical values for $f(\nu)$ are indicated in Table I.

Table I

Typical Values for $f(\nu)$

Fractional tune	$f(\nu)$
0.1	3.57
0.2	2.03
0.3	1.57
0.4	1.38
(0.5)	(1.33)
0.6	1.38
etc.	etc.

C. Variation with Phase Advance, Tune, Cell Size

To explore the sensitivity to the choice of phase advance, we can evaluate equations (1') - (3') for a range of the "traditional" values for μ, e.g., 60°, 90°, 108°. For equation (1') we find:

$\mu = 60°$

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} = 11.7\ f(\nu)\ \nu^{1/2}\ (\Delta Q)_{rms} \tag{12a}$$

$\mu = 90°$

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} = 12.5\ f(\nu)\ \nu^{1/2}\ (\Delta Q)_{rms} \tag{12b}$$

$\mu = 108°$

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} = 14.2\ f(\nu)\ \nu^{1/2}\ (\Delta Q)_{rms}\ . \tag{12c}$$

While equations (2') and (3') yield

$\mu = 60°$

$$\hat{x}_{\Delta B} = 4.3\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ \left(\frac{\Delta B}{B}\right)_{rms} \tag{13a}$$

$$\hat{y}_{\Delta\phi} = 4.3\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ (\Delta\phi)_{rms} \tag{14a}$$

$\mu = 90°$

$$\hat{x}_{\Delta B} = 4.9\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ \left(\frac{\Delta B}{B}\right)_{rms} \tag{13b}$$

$$\hat{y}_{\Delta\phi} = 4.9\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ (\Delta\phi)_{rms} \tag{14b}$$

$\mu = 108°$

$$\hat{x}_{\Delta B} = 5.8\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ \left(\frac{\Delta B}{B}\right)_{rms} \tag{13c}$$

$$\hat{y}_{\Delta\phi} = 5.8\ f(\nu)\ L_{cell}\ (m\nu)^{-1/2}\ (\Delta\phi)_{rms} \tag{14c}$$

We can see from the above exercise that the closed-orbit deviations are rather insensitive to the choice of μ and will therefore not significantly constrain the selection of this parameter. We note, however, that selection of a smaller phase advance does tend to minimize the expected closed-orbit errors. In addition, we note that equations (12)-(14) show only a weak (square root) dependence on the tune, of the machine. Because equation (12) depends on $\nu^{1/2}$, while equations (13) and (14) depend on $\nu^{-1/2}$, the preference (in our context) for a high or low tune will depend primarily on the relative magnitudes of the deviations predicted by equations (12) and (13) (horizontal) or (12) and (14) (vertical). For example, if the errors due to quadrupole displacement were dominant, a lower tune value would be preferred.

With regard to cell size, we see that the quadrupole displacement errors do not depend on this parameter, while errors involving the dipoles do. Inspection of equations (13) and (14) shows that the predicted deviations decrease as L_{cell} decreases and as the number of dipoles per cell increases. Thus, for a given μ, ν, and L_{cell}, it is better to have many independent dipoles than a few very large ones.

D. Numerical Example

In order to give a feeling for the possible deviations that might be encountered, we will evaluate the above expressions for a particular lattice. Relevant lattice parameters are given in Table II; a more complete description may be found in Ref. 3.

Table II

Representative SSC Lattice Parameters

$B_{max} = 6.5$ T

$\nu_x = \nu_y = 97.24$

$L_{cell} = 160$ m

Phase Advance, $\mu = 60°$

$\beta_{max} = 276$ m

$\beta_{min} = 93$ m

$M_B = 4032$

$M_Q = 1026$

$m = 8$ dipoles/cell

For this lattice $f(\nu) = 1.81$ and equations (12a) - (14a) become

$$\hat{x}_{\Delta Q} = \hat{y}_{\Delta Q} = 210\ (\Delta Q)_{rms} \tag{15}$$

$$\hat{x}_{\Delta B} = 45\ \left(\frac{\Delta B}{B}\right)_{rms}\quad (m) \tag{16}$$

$$\hat{y}_{\Delta\phi} = 45\ (\Delta\phi)_{rms}\quad (m) \tag{17}$$

Based on the experience at many accelerators, we tentatively assume that the quadrupoles can be aligned to an rms error of 0.2 mm in both the horizontal and vertical planes. (We will see below, however, that present techniques may make this horizontal alignment precision difficult to achieve.) To estimate the uncertainty in roll angle, we will assume that the magnet coils can be located in the cryostat to within about 12.5-25 µm. For a coil radius of 2.5-5 cm, this corresponds to an angular uncertainty of 0.5 mrad. Finally, we will assume that a dipole field error of 1×10^{-3} is a reasonable estimate for a typical medium-to-high-field superconducting magnet.

Given these estimated uncertainties, the maximum uncorrected closed-orbit distortions due to the various effects are:

$\hat{x}_{\Delta Q} = 42$ mm

$\hat{x}_{\Delta B} = 45$ mm

$\hat{y}_{\Delta Q} = 42$ mm

$\hat{y}_{\Delta\phi} = 22$ mm

Thus, without considerably improved alignment accuracy, the uncorrected beam would not be able to circulate within the 3-cm diameter aperture (~2-cm diameter "good field" region) of this SSC lattice. In order to have a reasonable possibility of circulating an uncorrected beam in the SSC, we would need to achieve tolerances a factor of 4 tighter than those assumed here--an expensive and perhaps impractical task. We note in passing that the maximum uncorrected orbit errors found here are similar in magnitude to those predicted[5] for the LEP machine at CERN.

The deviations predicted in this section are based on the properties of the regular part of the lattice. In the insertions, the betatron amplitudes are larger than those in the regular cells by about a factor of 6. Although there are many fewer quadrupoles in the insertions (120 vs. 1026) they are longer and stronger than the regular quadrupoles. For the same alignment tolerance, therefore, equation (1) predicts that the maximum deviation due to the insertion quadrupoles would be about 5 times that due to the regular quadrupoles.

E. Corrector Strengths

In general, we imagine that there will be a horizontal correcting dipole after each F quadrupole and a vertical correcting dipole after each D quadrupole. If we ask that each correction element compensate for the effects of the m/2 dipoles immediately upstream of itself, the m/2 dipoles immediately downstream, and the adjacent pair of quadrupoles, then we can estimate an average strength (for the horizontal plane) by

$$\langle\theta_{corr}\rangle_H \simeq \left[m \frac{\bar{\beta}}{\beta_{max}} \langle\Delta\theta_{dipole}\rangle^2 + \frac{(\Delta Q)^2_{rms}}{F^2} \left(\frac{\beta_{max}+\beta_{min}}{\beta_{max}}\right)\right]^{1/2} \qquad (18)$$

where $F = 1/K\ell_Q$ is the focal length in meters

and $\Delta\theta_{dipole} = \bar{\theta}_{dipole} \left(\frac{\Delta B}{B}\right)_{rms} = \frac{2\pi}{M_B}\left(\frac{\Delta B}{B}\right)_{rms}$.

Parametrizing equation (18) as before gives

$$\langle\theta_{corr}\rangle_H = \left[\frac{\mu^2}{m\nu^2(1+\sin(\mu/2))} \left(\frac{\Delta B}{B}\right)^2_{rms} + \frac{32\sin^2(\mu/2)}{L^2_{cell}(1+\sin(\mu/2))} (\Delta Q)^2_{rms}\right]^{1/2} \qquad (18')$$

For our traditional choices of phase advance equation (18') becomes:

$\nu = 60°$

$$\langle\theta_{corr}\rangle_H = \left[\frac{0.73}{m\nu^2}\left(\frac{\Delta B}{B}\right)^2_{rms} + \frac{5.3}{L^2_{cell}}(\Delta Q)^2_{rms}\right]^{1/2} \qquad (19a)$$

$\nu = 90°$

$$\langle\theta_{corr}\rangle_H = \left[\frac{1.5}{m\nu^2}\left(\frac{\Delta B}{B}\right)^2_{rms} + \frac{9.4}{L^2_{cell}}(\Delta Q)^2_{rms}\right]^{1/2} \qquad (19b)$$

$\nu = 108°$

$$\langle\theta_{corr}\rangle_H = \left[\frac{2.0}{m\nu^2}\left(\frac{\Delta B}{B}\right)^2_{rms} + \frac{11.6}{L^2_{cell}}(\Delta Q)^2_{rms}\right]^{1/2} \qquad (19c)$$

Thus, the average corrector strengths are significantly reduced for the smaller phase advance.

For the lattice example from Table II, equation (19a) gives

$$\langle\theta_{corr}\rangle_H = 4.2\ \mu rad$$

or $\langle B\cdot\ell\rangle_{corr,H} = 0.28$ T•m.

If we assume a maximum corrector requirement of ten times this amount, then the maximum corrector strength would be about 3 T•m. Here too, we find that the maximum corrector strength is comparable to that predicted[5] for LEP.

In the vertical plane, the average corrector strength is

$$\langle\theta_{corr}\rangle_V \simeq \left[m \frac{\bar{\beta}}{\beta_{max}} \langle\Delta\phi_{roll}\rangle^2 + \frac{(\Delta Q)^2_{rms}}{F^2} \left(\frac{\beta_{max}+\beta_{min}}{\beta_{max}}\right)\right]^{1/2} \qquad (20)$$

where $\Delta\phi_{roll} = \bar{\theta}_{dipole}(\Delta\phi)_{rms} = \frac{2\pi}{M_B}(\Delta\phi)_{rms}$.

This expression can be rewritten as

$$\langle\theta_{corr}\rangle_V = \left[\frac{\mu^2}{m\nu^2(1+\sin(\mu/2))} (\Delta\phi)^2_{rms} + \frac{32\sin^2(\mu/2)}{L^2_{cell}(1+\sin(\mu/2))} (\Delta Q)^2_{rms}\right]^{1/2} \qquad (20')$$

For μ values of 60°, 90°, 108°, this equation has the same numerical coefficients as equations (19a), (19b), and (19c), respectively. Using parameters from Table II, we get (analogous to (19a))

$$\langle\theta_{corr}\rangle_V = 3.3\ \mu rad \qquad (21)$$

or $\langle B\cdot\ell\rangle_{corr,V} = 0.22$ T•m.

III. Comments on Alignment Requirements

A. Vertical Alignment

In the case of vertical alignment, it may be possible to achieve higher precision than would be possible for horizontal alignment. The reason is that, in principle, gravity can be used as a reference, thus allowing "local" measurements whose accuracy is independent of the size of the machine. Whether such gains can be realized in practice, of course, is not yet fully clear. We note, however, that a liquid-level technique has been used[6] in the alignment of the PEP accelerator with satisfactory results.

The steering effect due to dipole roll should be reasonably controllable, because this can surely be handled with local measurements. Indeed, for a machine the size of the SSC a certain amount of roll will be necessary to compensate for the earth's curvature. For a machine radius R (in km), the required roll is

$$\Delta\phi = 0.156\ R\ \text{(mrad)}.$$

Depending on the technique utilized, measurements of quadrupole offsets may also be independent of machine size. This will be true, for example, if a liquid-level can be successfully used. If, on the other hand, traditional optical alignment methods are used, it is likely that the measured offsets will become less precise as the machine size increases. In particular, we would expect that the angular measurement error

$$\Delta\theta_Q = \frac{(\Delta Q)_{rms}}{F}$$

where F is the quadrupole focal length, would be roughly independent of accelerator size, rather than

$(\Delta Q)_{rms}$ itself.

From equations (1) and (3) we have

$$\frac{\hat{y}_{\Delta\phi}}{\hat{y}_{\Delta Q}} = \frac{2\pi}{(M_Q M_B)^{1/2}} \frac{1}{K\ell_Q} \frac{(\Delta\phi)_{rms}}{(\Delta Q)_{rms}} \quad (22a)$$

$$= \frac{2\pi(1+P)}{N_t P^{1/2}} \frac{(\Delta\phi)_{rms}}{(\Delta Q)_{rms}/F} \quad (22b)$$

where $P = M_Q/M_B$ and $N_t = M_Q+M_B$ is the total number of accelerator magnets. In the situation where both $\Delta\phi$ and $\Delta Q/F$ are independent of machine size, we can see from equation (22b) that the effect of dipole roll becomes less important (compared with that of quadrupole displacement) as the machine size, i.e., the number of magnets, increases.

For the Fermilab Tevatron, the dipole roll error, including the error due to marking the positions ("lug error") is

$$(\Delta\phi)_{rms} = \left[0.19^2 + 0.20^2\right]^{1/2} = 0.28 \text{ mrad},$$

while the quadrupole displacement error is

$$\frac{(\Delta Q)_{rms}}{F} = \frac{0.3 \text{ mm}}{27 \text{ m}} = 1.1 \times 10^{-2} \text{ mrad} \quad .$$

Also, for the Tevatron, P=0.25 and $N_t \sim 1000$. Equation (22b) then yields

$$\frac{\hat{y}_{\Delta\phi}}{\hat{y}_{\Delta Q}} = 0.40 \quad .$$

For the SSC lattice in Table II, P=0.25 and $N_t = 5058$ and we expect (for the same angular errors)

$$\frac{\hat{y}_{\Delta\phi}}{\hat{y}_{\Delta Q}} = 0.08 \quad .$$

If it turns out that $(\Delta Q)_{rms}$ is the appropriate constant, then we would expect

$$\frac{\hat{y}_{\Delta\phi}}{\hat{y}_{\Delta Q}} = 0.23 \quad .$$

i.e., still a factor of 2 better than the Tevatron.

With regard to quadrupole displacement, equation (1) shows that

$$\hat{y}_{\Delta Q} \propto M_Q^{1/2} (K\ell_Q)_{rms} (\Delta Q)_{rms} \quad (23a)$$

$$= M_Q^{1/2} \frac{(\Delta Q)_{rms}}{F} \quad . \quad (23b)$$

Thus, as the machine size (and hence M_Q) increases, the orbit distortion increases. From equation (20), however, we see that the required corrector strength depends on $\Delta Q/F$. As mentioned, if traditional alignment techniques are used, we expect $\Delta Q/F$ to be roughly constant, and thus the required corrector strength θ_{corr} will be similar to that of the Tevatron. (The field to accomplish the correction scales as $B\rho$, of course, and would require 20 times the $B\ell$ product of Tevatron correctors.) If it is possible, say by using a liquid-level measuring technique, to keep ΔQ constant, the required corrector strength would decrease for the larger SSC lattice (larger F).

Finally, equation (20) shows that the corrector strength required for dipole roll will decrease for the SSC compared with the Tevatron, because the number of dipoles is much greater for the SSC and the roll error itself should be roughly comparable (due to local measurement techniques being suitable).

B. Horizontal Alignment

It is likely in this case that local quadrupole-to-quadrupole misalignments will be the dominant source of closed-orbit error. Because standard survey and alignment techniques are likely to be used in this case, it is the ratio $\Delta Q/F$ that we expect to remain comparable to Fermilab results. We conclude, therefore, that the horizontal misalignments may be larger than those for the vertical plane (where "local" measurements may be usable).

C. Fermilab Tevatron Alignment Results

Fermilab used traditional optical methods (levels and theodolites) both to establish the monument system and to align the magnets. Random errors in the horizontal plane monuments, which, in turn, determine the design strength of the correction dipoles, were anticipated to be the dominant source of error. The quadrupole position error, $(\Delta Q_H)_{rms}$, was estimated to be 0.56 mm. This gives a contribution of 24 μrad to the average horizontal correction angle (see equation (18)). The contribution of the $1\text{x}10^{-3}$ rms variation in dipole field contributed another 18 μrad to equation (18), so that $\langle\theta_{corr}\rangle_H$ was predicted to be 30 μrad. This prediction is in excellent agreement with the observed rms bending angle in the horizontal correction dipoles (35 μrad) obtained after the orbit had been centered at all focusing quadrupoles.

In the vertical plane, $(\Delta Q_V)_{rms}$ was measured to be 0.30 mm after the machine was installed. Had greater care been been taken in controlling the elevation monuments, a lower value of 0.20 mm would have been achieved. (This has been demonstrated by partial data sets in which the monuments were well controlled.) Such care was not needed, however, as the vertical correction dipoles were designed to have the same strength as the horizontal correction dipoles, and thus were more than adequate to correct for an rms placement error of 0.30 mm. The rms dipole "roll" error--found to be 0.28 mrad, with equal contributions from installation error and the error in measuring and referencing the angle of the magnetic field to the alignment lugs on the outside of the magnet--made a negligible contribution to the required correction dipole strength. In equation (20), the roll term contributes 5 μrad, whereas the ΔQ term contributes 12 μrad to their geometric sum of 13 μrad. This predicted value is also in good agreement with the observed rms vertical correction magnet steering angle of 17 μrad necessary to center the beam at each vertically focusing quadrupole.

The conclusion of the Fermilab experience is that the known alignment errors lead to predictions of the required correction steering angles (equations 18 and 20) that are in good agreement with those observed. A second qualitative lesson is that, although the alignment was not good enough to achieve a closed orbit without the correction dipoles, the process of "coaxing" a low intensity beam around the ring was not difficult. It took only a few days of tuning to achieve the first turn.

D. Trade-offs

We recognize, of course, that an optimized design for the SSC will involve numerous trade-offs. In the area of concern to us here, a balance must be struck between the accuracy requirements and costs for survey and alignment compared with the difficulties and costs associated with the need for very high strength correction magnets. In evaluating these trade-offs, we feel that there does appear to be a practical limit to how poor the alignment can be: The alignment should be at least good enough to ensure that a beam that has been centered with the correction dipoles up to a certain quadrupole does not leave the bore tube for at least another cell. This criterion allows the beam to be corrected to centerline at the next monitor position without having to "fly blind." A crude calculation indicates that the offset at the next monitor position would be of the order of $5(\Delta Q)_{rms}$. Fortunately, even for (ΔQ_{rms}) values as large as 1 mm, this offset is quite small compared with the smallest SSC bore tube (25 mm diameter) presently being discussed.

IV. Conclusions

It seems clear, based on the considerations outlined here, that it will not be possible to achieve an "uncorrected" closed orbit without a substantial improvement in survey and alignment techniques. Although it may be possible to improve these techniques, it is by no means clear that the rewards would justify the effort and expense involved. Our suspicion is that both the magnets and the survey monuments would change position over time, so that even a machine initially aligned perfectly would ultimately require substantial correction. (This may also have implications on using the SSC for polarized beams. It appears[2] that maintaining beam polarization at high energies may lead to more exacting constraints for machine alignment (that is, allowable corrector strengths) than does the closed-orbit issue considered here.) If the alignment does change with time (as evidence from Fermilab seems to indicate), it appears to us much more practical to achieve a closed orbit in the SSC by "coaxing" a low energy, low intensity beam around the machine in sections. This approach has been shown to be effective at the Tevatron and will clearly simplify greatly the startup of the SSC.

The actual cost trade-offs between improved alignment techniques and stronger correction dipoles should be the subject of further study.

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