The Effect of Global Survey Misalignment on the SSC

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Abstract

Survey errors in the global alignment of the SSC can affect its performance. These errors can result in an uncertainty in the circumference of the Collider, and this can produce a mismatch in the transfer of bunches from the HEB to the SSC. An uncertainty in the half-circumference of the Collider will reduce the luminosity. To estimate this effect, an expression is given for the luminosity as a function of crossing angle and half-circumference difference. In addition, estimates are given for closed orbit distortion, vertical dispersion, and tune shift, resulting from circumferential errors. Suggestions are made for correcting the effects resulting from global survey errors. Further details may be found in [1].

I. INTRODUCTION

Performance of the Superconducting Super Collider (SSC) will require precision in global and local survey consistent with the survey precision required of individual components guiding the beam. Local transverse misalignment gives rise to a closed orbit error and a tune shift, and these effects should be within the range of the correctors. Survey errors also lead to an error in the circumference of the Collider, which has two consequences. The first is a mismatch in the circumferences of the High Energy Booster (HEB) and the Collider. Either this has to be compensated by moving the orbit of the HEB or the concomitant increase in longitudinal emittance has to be acceptable. The second is an error in the location of the detectors (half-cicumferential error) on opposite sides of the ring. The bunch crossing, if perfect on one side, will be mismatched on the other side, and this will lead to a reduction in luminosity, which has to be corrected by moving the interaction point where the mismatch occurs.

There are two principal contributions to survey errors. The first is the uncertainty in the location of the principal survey monuments, approximately 4.3 km apart, at the tunnel level. This uncertainty, resulting from the Global Positioning System and transfer to the tunnel level, is of the order $3\sigma \sim 15(22)$ mm, with(without) sight pipes,. The second is the positioning of the secondary monuments. Between the principal transfer monuments there are secondary monuments spaced at 30 m to 45 m apart. The locations of the secondary monuments have random errors with $\sigma \sim 0.5$ mm. Even after the initial survey, other misalignment errors can occur. Tunnel survey shows that the LEP transverse alignment is deteriorating approximately 140 μm per year [2]. In addition there can be a systematic radial error, as observed in HERA [3], due to horizontal refraction during angular measurement and inaccuracies in the self-centering of the theodolite and targets. This error, maximum value for HERA being 16 mm, is estimated to be 30-50 mm for the SSC.

II. CIRCUMFERENTIAL ERRORS

The arc length between two transfer monuments can be represented by

$$S(\theta_0) = \int_0^{\theta_0 \pm \delta\theta_0} \rho(\theta)[1 + (\frac{d\rho}{d\theta}/\rho(\theta))^2 + (\frac{dz}{d\theta}/\rho(\theta))^2]^{1/2} d\theta, \tag{1}$$

with radius $\rho(\theta) = \rho_0 + \epsilon_1 + \epsilon_2 sin(\pi\theta/\theta_0)$, where ϵ_1 (radial) and $\delta\theta_0$ (angular) are random errors, and ϵ_2 is the maximum systematic radial deviation. To first order, the error in the part of the circumference between two monuments is,

$$\Delta C(\theta_0) = \pm([(\epsilon_1\theta_0)^2 + (\rho_0\delta\theta_0)^2]^{1/2} \pm 2\epsilon_2\theta_0/\pi), \tag{2}$$

where $\theta_0 \sim \pi/N$ for N transfer monuments in each arc. The total uncertainty in the circumference resulting from the two Collider arcs is at least

$$\Delta C_{arcs} = \pm(\sqrt{2N}[(\epsilon_1\theta_0)^2 + (\rho_0\delta\theta_0)^2]^{1/2} \pm 4\epsilon_2). \tag{3}$$

With $\rho_0\delta\theta_0 \sim \epsilon_1\theta_0$, and $\epsilon_2 = 0$, (3) gives

$$\Delta C_{arcs} = 2\pi\epsilon_1/\sqrt{N}. \tag{4}$$

For $N = 8$, and $\epsilon_1 = 3\sigma$, one finds at the three sigma level $\Delta C_{arcs} = 33(49)$ mm, with(without) sight pipes, The random error could be reduced with additional transfer monuments. The systematic errors, however, could be the major source of circumferential error. For the case with $\epsilon_2 = 30 \rightarrow 50$ mm, one finds a systematic circumferential error $4\epsilon_2 \sim \pm(120 \rightarrow 200)$ mm, which should be added to the random error.

In a straight section, the ideal distance between transfer monuments is R_1. If one assumes an error vector $\vec{a}$ at each ideal location, then the vector distance between monument locations i and j is $\vec{r} = \vec{R_1} + \vec{a}_i - \vec{a}_j$. When averaged over

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the angles between the vectors, one finds the change in the distance between transfer monuments to be

$$r - R_1 \sim \frac{a^2}{R_1}. \quad (5)$$

For each straight section, the maximum systematic distance error resulting from the misalignment of N_1 pairs of transfer monuments would be $N_1 a^2/R_1$.

Between the transfer monuments, there are secondary monuments spaced at $R_2 \sim 30$ m apart. For N_2 pairs of secondary monuments with error vectors $\vec{b}$, the estimated distance error would be $N_2 b^2/R_2$. For both straight sections, the change in the circumference of the Collider resulting from systematic monument alignment error, would be

$$2N_1 a^2/R_1 + 2N_2 b^2/R_2.$$

For random alignment errors, N_1 and N_2 are replaced with $\sqrt{N_1}$ and $\sqrt{N_2}$, respectively. For values $a = 10$ mm, $b = 1.0$ mm, $R_1 = 4.3$ km, $R_2 = 30$ m, $N_1 = 20$, and $N_2 = 72$, there is a one sigma circumferential uncertainty of $\Delta C_{systematic} = 4.9\,\mu$m and $\Delta C_{random} = 0.63\,\mu$m.

III. CLOSED ORBIT ERROR

The closed orbit error due to transverse misalignment for N transfer monuments can be estimated from the formula, applicable to both transverse directions,

$$\Delta x_{rms} = \frac{\beta_{max}^{1/2}(\beta_{max}+\beta_{min})^{1/2}}{2\sqrt{2}sin(\pi\nu)}[\theta_{rms}]\sqrt{N/2}, \quad (6)$$

where θ_{rms} is the rms angular deflection resulting from monument alignment errors, and ν is the machine tune. With a three sigma alignment error, the deflection angle would be

$$\theta_{rms} = \frac{\sqrt{2}\times 3\sigma}{(C/N)}. \quad (7)$$

With $N = 20$, one finds $\theta_{rms} = 4.8(7)\,\mu$rad, with(without) sight pipes. For $\beta_{max} = 305$, $\beta_{min} = 54$, $\nu = 123.28$, and $N = 20$, one finds the random closed orbit error $\Delta x_{rms} = 2.3(3.4)$ mm, with(without) sight pipes, at the three sigma level for monument alignment errors.

As a result of surveying methods, systematic tilt errors in the alignment of the magnets are not expected; however, there is a possibility of systematic radial alignment error in the location of the monuments and the magnets. If there is a transverse systematic radial change along the ideal orbit of the form $\rho = \rho_0 + \epsilon_2 sin(\pi s/s_0)$, where s is the ideal orbit length and s_0 is the length over which the systematic error of maximum deviation ϵ_2 occurs, then the angle which must be corrected is

$$\theta_c \sim 2d\rho/ds|_{\theta=0} = \epsilon_2 2\pi/s_0. \quad (8)$$

For $s_0 = 4.3$ km and $\theta_c \sim 45\mu$rad, this permits a maximum deviation of $\epsilon_2 \sim 30$ mm. There are corrector magnets in each cell to correct for this effect.

If there is a systematic uncertainty in the vertical alignment of the transfer monuments, a vertical correction bend of order

$$\theta_c \sim 4D/s_0$$

would be required. For a systematic vertical error of ϵ at each of N monuments, the maximum vertical deviation would be $D = N\epsilon/2$. For an arc, $N \sim 10$, $\epsilon \sim 10$ mm, and $s_0 = 35$ km; thus a correction of $\theta_c \sim 5.7\mu$ rad would be required. Between transfer monuments of separation $s_0 \sim 4.3$ km there are approximately 143 secondary monuments. If $\epsilon \sim 1.0$ mm for each secondary monument, then a vertical steering correction of 67μ rad would be required. One sees that systematic vertical alignment errors require steering correction; however, there are steering correctors in each cell to correct for this effect.

With vertical misalignment we expect a contribution to vertical dispersion. The equation for the dispersion is,

$$D''(s) + K(s)D(s) = 1/\rho. \quad (9)$$

If $\rho_y = Q_0\rho_0$, then $D_y(s) \sim Q_0{}^{-1}D_x(s)$. For a vertical arc of sagitta d and length s_0, the radius of curvature is $\rho_y \sim \frac{s_0^2}{8d}$. With $d \sim 100$ mm, $s_0 \sim 4.3$ km, and $\rho_0 \sim 12$ km, we find $Q_0 \sim 2\times 10^3$, which is negligible.

The tune shift associated with a circumferential error is

$$\delta\nu \sim \frac{\Delta C}{2\pi\bar{\beta}} = .44\times 10^{-4}, \quad (10)$$

where $\bar{\beta} = 180$ m and $\Delta C = 5\times 10^{-2}$ m.

IV. LUMINOSITY

We assume gaussian bunches of distribution $\rho(x, y.x)$ with standard deviations σ_x, σ_y and σ_z, with z along the orbit. For n_b bunches of circulation period T_0, with N_B protons in each bunch, crossing angle 2α, and speed v relative to the interaction point, the luminosity, which depends on the difference in half-circumference δ, is

$$\mathcal{L}(\alpha,\delta) = 2vcos(\alpha)\frac{n_b}{T_0}\int \rho_1(x_1,y_1,z_1)\rho_2(x_2,y_2,z_2)dxdydzdt. \quad (11)$$

For bunches, which cross at an angle α relative to the z axis and which have a distance δ between their centers when one bunch center is at the interaction point, the coordinates of the two bunches are

$$\begin{aligned} x_1 &= x_2 = x \\ y_1 &= zsin(\alpha) + ycos(\alpha) \\ y_2 &= -zsin(\alpha) + ycos(\alpha) \\ z_1 &= zcos(\alpha) - ysin(\alpha) - vt \\ z_2 &= zcos(\alpha) + ysin(\alpha) + vt - \delta. \end{aligned} \quad (12)$$

Integration gives,

$$\mathcal{L}(\alpha,\delta) = \frac{N_B^2 n_b}{T_0}\frac{e^{-[(\frac{\delta}{2\sigma_z})^2(1+(\frac{\sigma_y cot(\alpha)}{\sigma_z})^2)^{-1}]}}{4\pi\sigma_x\sigma_y cos(\alpha)\sqrt{1+(\frac{\sigma_z tan(\alpha)}{\sigma_y})^2}}. \quad (13)$$

As a measure of the overlap of the bunches we define the luminosity efficiency $R(\delta) = \mathcal{L}(\alpha,\delta)/\mathcal{L}(\alpha,0)$, which is

$$R(\delta) = 100 \times exp[-(\frac{\delta}{2\sigma_z})^2(1+(\frac{\sigma_y cot(\alpha)}{\sigma_z})^2)^{-1}]\%. \quad (14)$$

For $\beta^* = 0.5$ m, $R(\delta = 50\,\mathrm{mm}) = 97.13\%$ and $R(\delta = 100\,\mathrm{mm}) = 89.14\%$. For $\beta^* = 10$ m, $R(\delta = 50\,\mathrm{mm}) = 99.8\%$ and $R(\delta = 100\,\mathrm{mm}) = 99.3\%$.

The luminosity can be restored at one interaction point, preferably low β, with RF manipulations. The final focusing quadrupole magnets can move the interaction point approximately one meter within the detector.

V. BEAM TRANSFER FROM THE HEB

To match the bunches from the HEB to the buckets in the Collider, it may be necessary to move the closed orbit from its center. The Collider circumference (87.12km) is approximately eight times the HEB circumference (10.8km). It is better to move the HEB orbit and to keep the Collider orbit at its center. If the error in the Collider circumference is ΔC_{HEB}, then the error in the mean radius is $\Delta\bar{r}_{HEB} = \Delta C_{Coll}/16\pi$. For $\Delta C_{Coll} = 50$ mm, one finds $\Delta\bar{r}_{HEB} = 1.5$ mm. Since $\alpha_{HEB} = 9.1 \times 10^{-5}$, and $(\Delta p/p)_{HEB} \sim 4.9 \times 10^{-4}$, the peak radial excursion of the closed orbit of the HEB would be $\delta\hat{r}_{HEB} \sim 1.5$ mm, with $\eta_{HEB} = 3.1$ m. This is marginally acceptable.

Alternatively we may use the circumferential discrepancy to accomplish fine cogging. If the circumferences of the two machines are perfect, assigned buckets in the two machines can be brought within a distance of 360 meters. Further alignment, called fine cogging, is accomplished by introducing a mismatch, made zero at extraction, in the machine circumferences. Mismatch in the central orbit could be used to do this fine cogging with a difference that it is not brought to zero at extraction. If the slippage rate, due to surveying error, is comparable to 114 buckets/sec, which corresponds to a slippage rate of one-half bucket in fifteen turns in the Collider, then the fine cogging can be done in ~ 1.3 seconds.

Here we have to accept the mismatch and resulting dilution of the longitudinal emittance. The latter is found from

$$\Delta\epsilon_l/\epsilon_l = \frac{1}{2}(\Delta z/\sigma_z)^2. \quad (15)$$

If the central bunch in a train from the HEB is centered on an RF bucket in the Collider, then there will be an error in the position of the end bunches relative to a bucket center in the Collider of the order

$$\Delta z = \Delta C_{Coll}(C_{HEB}/C_{Coll}). \quad (16)$$

For $\Delta C_{Coll} = 50$ mm, and $\sigma_z = 70$ mm, the longitudinal emittance dilution is $\Delta\epsilon_l/\epsilon_l \sim 0.39\%$, which is a small effect.

The change in the RF frequency due to the circumferential error is $\Delta f/f = \Delta C_{Coll}/C_{Coll}$. For $\Delta C_{Coll} \sim 50$ mm, one finds $\Delta f/f = 0.57 \times 10^{-6}$. For the Collider RF cavity, the nominal operating frequency is 360 MHz, and $\Delta f \sim 205$ Hz, which is within the tuning range, 50kHz, of the RF cavity.

VI. CONCLUSIONS

It appears that a global tunnel survey with the use of sight pipes would be desirable in achieving the ideal design requirements for the Collider. Although random errors of the order of $3\sigma \sim 15 \rightarrow 22$ mm in the transverse alignment of the transfer monuments at the tunnel level would appear to contribute not more than a 50 mm error at the three σ level to the circumference of the Collider, a systematic error of the type observed at HERA could contribute as much as $120 \rightarrow 200$ mm to the circumference. The detectors can accommodate an uncertainty of the order of $\sigma_z \sim 70$ mm in the location of the interaction point, and the interaction point can be moved up to one meter with tuning of the final focusing quadrupole magnets.

If sight pipes are used for the global survey, certain locations of these pipes would aid in the precision achieved in alignment. Sight pipes located at the ends of the straight sections would reduce the initial angular errors, which can occur in surveying the arcs. In addition, it would be helpful to locate sight pipes at arc midpoints and at the interaction points.

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VII. REFERENCES

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