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# The Effect of Global Alignment Survey Errors on the Performance of the Super Collider

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## I. INTRODUCTION

To meet the physics requirements for alignment of the tunnel transfer monuments, it appears that the use of sight pipes is desirable. A sight pipe provides a vertical line of sight for the transfer of surface survey monument coordinates to the tunnel level. A principal surveying constraint on the SSC is that the circumference should not deviate from the design value by more than 50 mm [1]. This is to allow, using the baseline scheme, a proper transfer of particle bunches from the HEB to the Collider[2]. The effect of errors in circumference on the HEB and Collider cogging scheme for bunch transfer is discussed in Appendix C. An additional requirement is that the difference in the half-circumference for each half of the Collider connecting two interaction points must not exceed 50 mm [3]. For $\beta^* = .5$ m, the luminosity efficiency ratio is 97% with a 50 mm difference in half-circumference and 89% with a 100 mm difference in half-circumference, and the corresponding values for $\beta^* = 10$ m are 99.8% and 99.3%. These are requirements for

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the global survey, which gives knowledge of distances longer than 1000 m. At present the value for the uncertainty in the transverse location of the principal survey monuments at the tunnel level is of the order[4]

$$3\sigma \sim 15\,\text{mm}, \text{ with sight pipes,}$$

$$3\sigma \sim 22\,\text{mm}, \text{ without sight pipes.}$$

This includes the uncertainties in the GPS(Global Positioning System) surface monument locations and the uncertainties resulting from transfer to the tunnel level. A systematic radial error at the three sigma level would result in a circumferential error of approximately $2\pi 3\sigma$. A random error in the location of the $N$ transfer monuments per arc would result in a circumferential error of approximately $2\pi 3\sigma/\sqrt{N}$.

High precision in global alignment is necessary for proper performance of the Super Collider. Tunnel survey shows that the LEP transverse alignment is deteriorating at about 140 $\mu$m per year[5]. Also, as shown in Fig. 1, there appears to be a slowly increasing systematic radial error, which increases to a maximum value of 16 mm [6], in each sector of HERA . This error could result from horizontal refraction during angular measurement or from inaccuracies in the self-centering of the theodolite and targets. A similar error between transfer monuments in the Collider could result in a maximum radial increase of 30 to 50 mm. In this note estimates are made of three sigma level global alignment error effects on Collider performance. Parameters are taken from the SSC Parameters List, 17 January 1992. The method used for combining systematic or random errors is discussed in Appendix A.

Without the precision achieved with sight pipes for global alignment, it could be difficult to achieve some of the tolerances required for proper Collider performance. At 20 TeV, steering corrections of $\sim 45\mu$rad in both the radial and vertical direction can be made within a 90 m half-cell. It is important that the magnets are aligned along a smooth path. The quadrupoles must be aligned with a one sigma value of .45 mm [7]. The closed orbit error and vertical dispersion caused by global transverse alignment

errors of the order $3\sigma \sim 15 \rightarrow 22$ mm at the transfer monuments can be accommodated with the present steering corrector dipoles; however, when coupled with systematic alignment errors between transfer monuments of the type observed at HERA, the present global alignment errors could make it difficult to preserve the 50 mm tolerance in the Collider circumference.

There is also a requirement that the difference between the circumferences of the two Collider rings should not differ by more than $\Delta C = C\alpha\Delta E/E$ [8], where $\alpha$ is the compaction factor and $\Delta E$ is the energy difference between the two rings. For $C \sim 87$ km, $\alpha \sim 9 \times 10^{-5}$, and $\Delta E/E \sim 10^{-4}$, one finds $\Delta C = 0.8\,\mathrm{mm}$.

## II. ARC CIRCUMFERENTIAL ERROR

In the Collider arcs, the distance between principal monuments when transferred to the tunnel level is approximately 4.3 km. Between the principal transfer monuments there are secondary monuments spaced at 30 m to 45 m apart. The one $\sigma$ uncertainty in the location of these monuments is approximately .5 mm. These errors, along with a systematic error of the type observed at HERA, could result in a Collider circumferential error greater than the allowed 50 mm.

The arc length between two transfer monuments can be represented by

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

The radius $\rho(\theta)$ is represented as

$$\rho(\theta) = \rho_0 + \epsilon_1 + \epsilon_2 sin(\pi\theta/\theta_0),$$

where $\epsilon_1$ represents the radial uncertainty, $\delta\theta_0$ the angular uncertainty, and $\epsilon_2$ the maximum value of the slow systematic radial deviation. Keeping terms of first order only, one finds the change in the circumference between monuments to be

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

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

$$\Delta C_{arcs} = 33\,\text{mm}, \text{ with sight pipes,}$$

$$\Delta C_{arcs} = 49\,\text{mm}, \text{ without sight pipes.}$$

This random error could be made smaller with the addition of more transfer monuments, i.e. larger $N$. Any systematic errors resulting from refraction effects could be the major source of circumferential error. For the case with $\epsilon_2 = 30 \rightarrow 50$ mm, one finds a systematic circumferential error

$$4\epsilon_2 \sim \pm(120 \rightarrow 200) \text{ mm},$$

which should be added to the random error.

## III. STRAIGHT SECTION CIRCUMFERENTIAL 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 the angles between the vectors, one finds the change in the distance between transfer monuments to be

$$r - R_1 \sim \frac{a^2}{R_1}. \tag{5}$$

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, $N_1 = 2$, and $N_2 = 72$, there is a one sigma circumferential uncertainty of of

$$\Delta C_{systematic} = 4.9\,\mu\text{m}$$
$$\Delta C_{random} = .63\,\mu\text{m}.$$

These are negligible when compared with the uncertainties resulting from transverse alignment errors in the arcs.

## IV. CLOSED ORBIT ERROR

The closed orbit error resulting from transverse alignment errors for $N$ transfer monuments can be estimated from the formula [9], which applies to both vertical and horizontal misalignments,

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

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

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

For $N = 20$, one finds

$$\theta_{rms} = 4.8\,\mu\,\mathrm{rad}, \text{ with sight pipes,}$$

$$\theta_{rms} = 7.0\,\mu\,\mathrm{rad}, \text{ without sight pipes.}$$

For $\beta_{max} = 305$, $\beta_{min} = 54$, $\nu = 123.28$, and $N = 20$, one finds the random closed orbit error

$$\Delta x_{rms} = 2.3\,\mathrm{mm}, \text{ with sight pipes,}$$

$$\Delta x_{rms} = 3.4\,\mathrm{mm}, \text{ without sight pipes,}$$

at the three sigma level for monument alignment errors. This is within the correction range of dipole corrector magnets, which is $45\mu$rad at 20 TeV and 10 times this value at 2 TeV.

As a result of vertical alignment 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 arc length and $s_0$ is the length over which the systematic error of maximum deviation $\epsilon_2$ occurs, then the angle which must be corrected is

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

For $s_0 = 4.3$ km and $\theta_c \sim 45\mu$rad, this permits a maximum deviation of $\epsilon_2 \sim 30$ mm with a single steering correction. This would be the worst case, for there are corrector magnets in each cell.

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 $\epsilon$ 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 $67\mu$ rad would be required. One sees that systematic vertical alignment errors require steering correction; however, there are steering correctors in each cell to correct this effect.

With vertical alignment errors one could expect a contribution to vertical dispersion. The differential equation for the dispersion function $D_{x,y}(s)$ is

$$D''(s) + K(s)D(s) = 1/\rho. \tag{9}$$

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 arc length $s_0$, the radius of curvature is

$$\rho_y \sim \frac{s_0^2}{8d}. \tag{10}$$

With $d \sim 100$ mm, $s_0 \sim 4.3$ km, and $\rho_0 \sim 12$ km, one finds $Q_0 \sim 2 \times 10^3$, so that vertical dispersion is very small.

An additional effect associated with a circumferential error is a small tune shift. This is given by

$$\delta\nu \sim \frac{\Delta C}{2\pi\bar{\beta}}. \tag{11}$$

For $\bar{\beta} = 180$ m and $\Delta C = 5 \times 10^{-2}$ m, this gives $\delta\nu = .44 \times 10^{-4}$.

## V. LUMINOSITY EFFICIENCY RATIO

The design luminosity is a critical parameter for the SSC. If the half-circumference in the north-half and south-half of the Collider differ, then oppositely moving bunches, which start from a given interaction point $A$, will not properly meet at the interaction point $B$ at the end of each half-circumference. This will result in reduced

luminosity at the interaction point $B$. As a measure of the overlap of the Gaussian bunches at the interaction point $B$, it is useful to define the luminosity efficiency ratio $R(\delta)$,

$$R(\delta) = 100 \times \mathcal{L}(\alpha, \delta)/\mathcal{L}(\alpha, 0)\,\%, \tag{12}$$

where $\alpha$ is the bunch crossing angle and $\delta$ is the difference between each half-circumference. For Gaussian longitudinal bunches of transverse standard deviations $\sigma_x$, $\sigma_y$, and longitudinal standard deviation $\sigma_z$, one finds, following the method of Appendix B,

$$R(\delta) = 100 \times exp[-(\frac{\delta}{2\sigma_z})^2(1 + (\frac{\sigma_y cot(\alpha/2)}{\sigma_z})^2)^{-1}]\,\%. \tag{13}$$

The effects on the luminosity resulting from a mismatch in half-circumferences are as follows:

$$R(\delta = 50\,\mathrm{mm}) = 97.13\%$$
$$R(\delta = 100\,\mathrm{mm}) = 89.14\%,$$

with $\beta^* = .5$ m, and

$$R(\delta = 50\,\mathrm{mm}) = 99.8\%$$
$$R(\delta = 100\,\mathrm{mm}) = 99.3\%,$$

with $\beta^* = 10$ m. The luminosity can be restored by changing the RF phase in each ring of the Collider. The interaction point can be moved up to one meter with tuning of the final focusing quadurpoles.

## VI. CONCLUDING REMARKS

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 $\sigma$ 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 1 meter with the tuning of the final focusing triplets.

Another consideration resulting from an error in the Collider circumference is the mismatch of bunch centers during transfer from the HEB to the Collider. If the error in the Collider circumference is $\Delta C_{Coll}$, then the error in the mean radius is $\Delta\bar{r}_{Coll} = \Delta C_{Coll}/2\pi$. For $\Delta C_{Coll} = 50$ mm and $\alpha_{Coll} = 9.1 \times 10^{-5}$, one finds $\Delta\bar{r}_{Coll} = 8$ mm. Since

$$\Delta\bar{r}_{Coll}/\bar{r}_{Coll} \sim \alpha_{Coll}\Delta p/p, \tag{14}$$

one finds $\Delta p/p \sim 6.3 \times 10^{-3}$. Along with this is a peak radial excursion of $\delta\hat{r} \sim \eta_{Coll}\Delta p/p \sim 11.3$ mm, with $\eta_{Coll} = 1.8$ m. This is outside the dynamic aperture of the Collider, which is $\sim 4$ mm. Therefore, any adjustments required for proper bunch transfer should be made by changing the closed orbit of the HEB.

If the error in the Collider circumference is 50 mm, the mean radius of the HEB closed orbit could be changed to make bunch spacing match for transfer from the HEB to the Collider. Since

$$\Delta\bar{r}_{HEB}/\Delta\bar{r}_{Coll} = \Delta C_{HEB}/\Delta C_{Coll}, \tag{15}$$

and

$$(\Delta p/p)_{HEB} = (1/\alpha_{HEB})\Delta\bar{r}_{HEB}/\bar{r}_{HEB} \sim 4.9 \times 10^{-4},$$

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.

If one prefers not to use the above procedure, then another concern resulting from a circumferential error in the Collider would be the dilution of the longitudinal emittance. This is found from

$$\Delta\epsilon_l/\epsilon_l = \frac{1}{2}(\Delta z/\sigma_z)^2. \tag{16}$$

If the uncertainty in the circumference of the Collider is $\Delta C_{Coll}$, then there will be an mismatch of the bunches transferred from the HEB to the Collider. 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

$$\Delta z = \Delta C_{Coll}(C_{HEB}/C_{Coll}). \tag{17}$$

For $\Delta C_{Coll} = 50$ mm, and $\sigma_z = 70$ mm, the longitudinal emittance dilution is $\Delta\epsilon_l/\epsilon_l \sim .39\%$, which is a small effect.

As a final remark, we consider the error in the Collider circumference, which can be corrected by tuning the RF cavity of operating frequency $f$. The change in the RF frequency is related to the circumferential error according to

$$\Delta f/f = \Delta C_{Coll}/C_{Coll}. \tag{18}$$

For $\Delta C_{Coll} \sim 50$ mm, one finds $\Delta f/f = .57 \times 10^{-6}$. For the Collider RF cavity, the nominal operating frequency is 360 MHz, and $\Delta f \sim 205$ Hz. This is within the tuning range of the RF cavity, which is 50 kHz.

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.

We have received valuable technical suggestions from D. Larson, M. Syphers and R. Wilkins.

## APPENDIX A. RANDOM WALK

The method of combining systematic or random errors can be understood from a study of a random walk model. For m steps of length $\sigma$ to the right and $N - m$ to the left, the distance traveled in $N$ steps is

$$D = m\sigma - (N - m)\sigma = (2m - N)\sigma. \qquad (A1)$$

If the probability for a step to the right is $p$ and to the left is $q = 1 - p$, then the probability for $m$ steps to the right and $N - m$ steps to the left is $P_N(m) = \binom{n}{m} p^m q^{N-m}$. The mean value and second moment of $m$ are

$$\bar{m} = Np$$
$$\bar{m^2} = \bar{m}^2 + Npq.$$

The mean value and variance(rms value) of $D$ are

$$\begin{aligned} \bar{D} =& (2p - 1)N\sigma \\ \sigma(D) =& [\bar{D^2} - \bar{D}^2]^{1/2} = \sqrt{N4pq}\sigma. \end{aligned} \qquad (A2)$$

For a systematic displacement, $p = 1$, $\bar{D} = N\sigma$, and $\sigma(D) = 0$. For a random displacement, $p = q = 1/2$, $\bar{D} = 0$, and $\sigma(D) = \sqrt{N}\sigma$.

## APPENDIX B. LUMINOSITY

For $n_b$ bunches of circulation period $T_0$ with $N_B$ protons in each bunch, which cross at an angle $\alpha$ and have speed $v$ relative to the interaction point, the luminosity, which depends on the difference in half-circumference $\delta$, is

$$\mathcal{L}(\alpha,\delta) = 2vcos(\alpha/2)\frac{n_b}{T_0}\int \rho_1(x_1,y_1,z_1)\rho_2(x_2,y_2,z_2)dxdydzdt. \tag{B1}$$

For Gaussian bunches, the particle density functions are

$$\rho_i(x_i,y_i,z_i) = \frac{N_B}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}e^{-\frac{x_i^2}{2(\sigma_x)^2}}e^{-\frac{y_i^2}{2(\sigma_y)^2}}e^{-\frac{z_i^2}{2(\sigma_z)^2}}, \tag{B2}$$

where the transverse standard deviations are $\sigma_x$ and $\sigma_y$, and the longitudinal standard deviation along the beam direction is $\sigma_z$. For bunches, which cross at an angle $\alpha/2$ relative to the $z$ axis and which have a distance $\delta$ between their centers when one bunch center is at the interaction point, the coordinates of the separate bunches are

$$\begin{aligned} x_1 &= x \\ y_1 &= zsin(\alpha/2) + ycos(\alpha/2) \\ z_1 &= zcos(\alpha/2) - ysin(\alpha/2) - vt, \end{aligned} \tag{B3}$$

and

$$\begin{aligned} x_2 &= x \\ y_2 &= -zsin(\alpha/2) + ycos(\alpha/2) \\ z_2 &= zcos(\alpha/2) + ysin(\alpha/2) + vt - \delta. \end{aligned} \tag{B4}$$

Upon integration, one finds the luminosity as a function of crossing angle and difference in half-circumference to be,

$$\mathcal{L}(\alpha,\delta) = \frac{N_B^2 n_b}{T_0}\frac{e^{-[(\frac{\delta}{2\sigma_z})^2(1+(\frac{\sigma_y cot(\alpha/2)}{\sigma_z})^2)^{-1}]}}{4\pi\sigma_x\sigma_y cos(\alpha/2)\sqrt{1+(\frac{\sigma_z tan(\alpha/2)}{\sigma_y})^2}}. \tag{B5}$$

## APPENDIX C. COGGING WITH CIRCUMFERENTIAL ERRORS

The synchronization between accelerators required for bunch transfer, "cogging", is usually performed with locking the separate bucket frequencies together. An additional synchronization, resulting from shifting relative bucket positions, "fine cogging", is needed. To accomplish frequency lock between the Collider and the HEB, when the two circumferences differ from the ideal values due to construction and survey errors, it will be necessary to shift the beam in the HEB away from the design center-line by and average shift in radius $\Delta\bar{r}$,

$$\Delta\bar{r} = \frac{1}{2\pi}(\Delta C_{HEB} \pm \Delta C_{Coll}/8). \qquad (C1)$$

The sign depends upon the sign of the two circumferential errors, and the factor 1/8 represents the ratio $(\Delta C_{HEB}/\Delta C_{Coll})$. For $\Delta C_{Coll} = 50\,\text{mm}$ and $\Delta C_{HEB} = 50/8\,\text{mm}$, the required $\Delta\bar{r}$ is 2.0 mm, and the corresponding $\delta p/p$ is $1.38 \times 10^{-3}$. This $\Delta\bar{r}$ is the maximum allowed in the HEB, with the current design. Since frequency lock can not be guaranteed with larger circumferential errors, the specification for the circumferential errors should be

$$\Delta C_{Coll} \leq 50 \text{ mm}$$

and

$$\Delta C_{HEB} \leq 6.25 \text{ mm}.$$

There is a method, using a modified cogging scheme, for accommodating larger circumferential errors than those specified above. This method is "cogging on the fly", and it has been proposed for LEB to MEB bunch transfer [10]. For this method, the beams in both machines run on their center-lines, which calls for RF frequencies that differ from the nominal $hf_0$ by $hf_0\Delta C/C$. For example, if $\Delta C_{Coll} = 100$ mm and $\Delta C_{HEB} = 12.5$ mm, then this difference is approximately 69 MHz in each ring. Thus, if the errors are such that the difference frequencies add, then there is a bucket slippage

between the two rings of 138 buckets/sec. This slippage can be used to achieve the fine cogging required. This follows from the fact that the maximum fine cogging required is a shift of 144 buckets, which requires a multi-step RF manipulation. 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 $\sim 1.3$ seconds.

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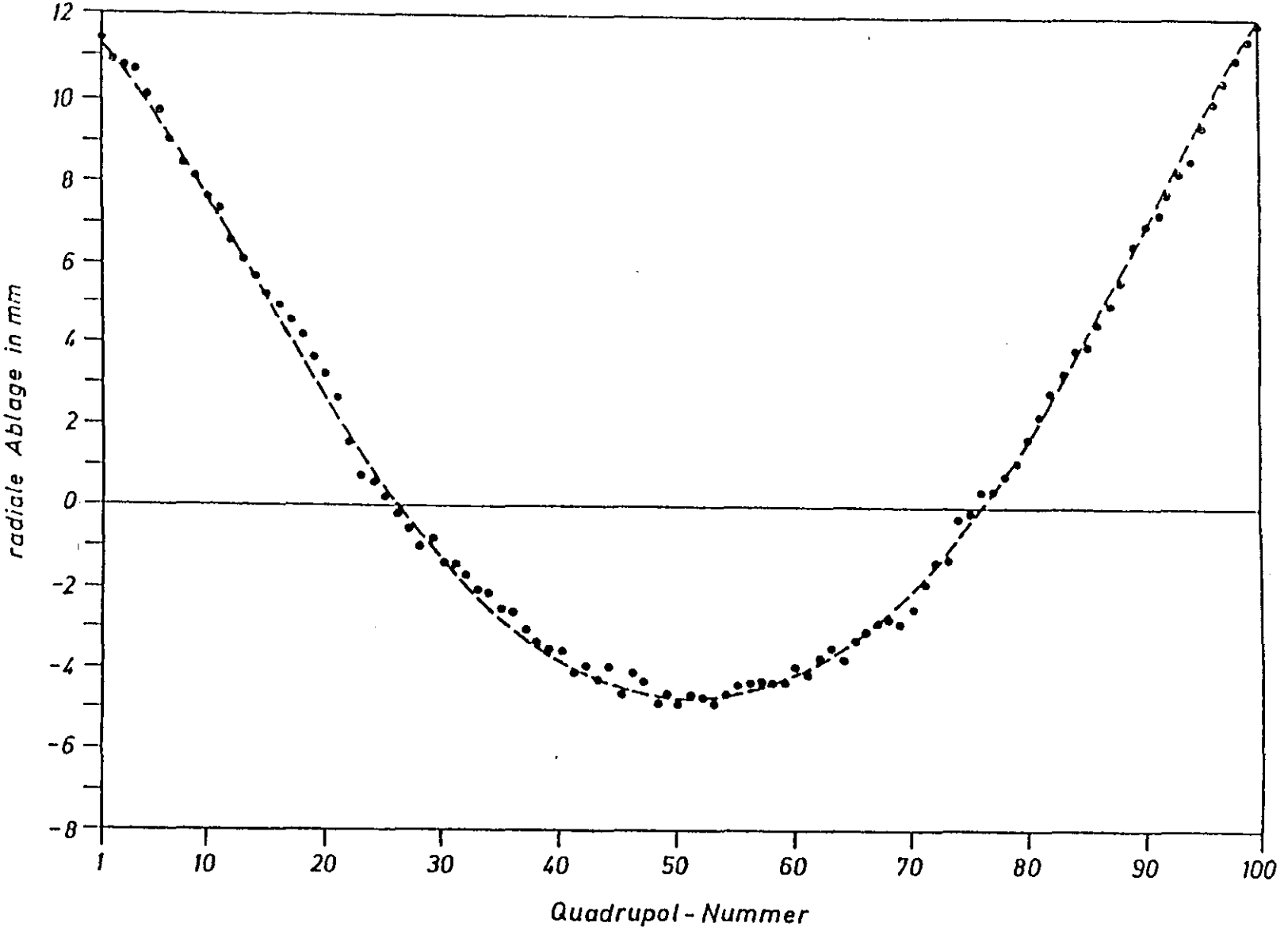


FIG.1. The HERA sector radial alignment systematic deformation, Ref.[6], p. 124 and Fig. 20.