TRACKING STUDIES ON THE EFFECTS OF RANDOM MULTIPOLES IN THE 6.5 T LATTICE OF THE SSC REFERENCE DESIGNS STUDY*

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Abstract

The acceptance of lattice A (6.5 T) of the SSC Reference Designs Study is determined for ten different sets of random errors as various multipole orders are set to zero. On the basis of 400 turn studies it is concluded that all multipole orders in the dipoles are important. Further studies show that the beam crossing dipoles limit the acceptance--when their multipoles are scaled as $r^{-(n+1)}$, corresponding to an increased coil radius, the acceptance of the lattice essentially doubles.

Introduction

Although a systematic study of several test lattices for the Superconducting Super Collider (SSC) has been initiated, it is still considered interesting to investigate further the aperture limitation resulting from random multipoles used for the Design A lattice (6.5 T) of the SSC Reference Designs Study (RDS). The motivation for this study was based on the possibility that time may be saved by spending a little more effort to understand a lattice that has already been studied extensively. The investigation described in this paper involves accessing the effect on the acceptance of removing multipoles of various orders.

The study is made as an extension of the work performed on the Design A lattice for the RDS¹. This results in accepting less than ideal conditions, but it at least makes the results of this paper directly comparable with the results reported in the RDS. In particular, the tracking studies made for the RDS considered the effects of special sextupoles suggested by Tom Collins and compared the acceptance with these sextupoles with the acceptance obtained without these sextupoles. The Collins scheme required that nine cells on either side of the insertions have a total phase advance of 4π . The strengths of the quadrupoles in these cells remained fixed; tuning was accomplished by changing the strengths of the quadrupoles in the remaining cells. There was a mismatch at the juncture of the tuning cells and the cells containing the special Collins sextupoles. When the Collins sextupoles were replaced by ordinary, chromaticity correcting sextupoles, the strengths of the quadrupoles in the special cells remained unchanged. This was done so that only one variable at a time would be changed; it is recognized that this is not the optimum configuration of the lattice.

In an effort to be consistent with past studies, the quadrupole strengths are the same as they were for the RDS. Thus the phase advance of the nine cells on each side of every insertion is 80° , and tuning has been performed with the remaining cells.

The emittances in the x and y directions are equal. During tracking, tests were made throughout the cells to determine whether the particle had exceeded a radial distance of 15 mm from the reference orbit. In all other elements (insertions plus utility straight sections) the radial test was set at 1000 mm.

The random multipoles are those used for tracking

the Design A lattice of the RDS. With the exception of a_1 and b_1 of the dipoles, they are listed in Table 5.1.1-6 on p. 187 of the RDS. The a_1 and b_1 used for tracking are one tenth of the values listed in the table. The reduction in the strength of these multipoles was justified with the argument that their effect could be reduced by 90% with appropriate magnet shuffling.

Acceptance Studies

The present studies were made on the CRAY 1-S and the CRAY X-MP computers at LLNL. In all studies the default CRAY random number generator was used. All acceptance determinations were made for ten different random number sequences. Magnet errors were selected from a gaussian distribution truncated at $\pm 3\sigma$. In all cases the quadrupoles in the tuning cells were adjusted to restore the tune to its nominal value of $\nu_x = 97.859$, $\nu_y = 97.869$. Two families of sextupoles were used to set the x and y chromaticities to zero at $\Delta P/P = 0.0\%$.

The acceptance was determined at $\Delta P/P = 0.0\%$ using 400 turn tracking runs. The initial amplitude of the test particle was increased in increments of 0.3 mm at the center of the regular cell quadrupoles until a point was reached where the particle was lost within 400 turns at one amplitude but survived 400 turns at three consecutive lower amplitudes. The acceptance was considered to lie between the largest stable amplitude and the amplitude at which the particle was lost. The bars representing the data points in the figures indicate this range of uncertainty.

In the first study, all dipole errors (a_n, b_n) with $1 \leq n \leq 6$ were included, and the effect of a skew quadrupole error ($a_1(\text{quad}) = 0.046 \text{ m}^{-1}$) resulting from an assumed rms quadrupole rotation of 1 mradian was determined for two cases: 1). $a_1(\text{quad}) = 0.046 \text{ m}^{-1}$ in all quadrupoles, and 2). $a_1(\text{quad}) = 0.0$ in all quadrupoles. The results of this determination are plotted in Fig. 1. Some random number sequences give acceptances of nearly zero, but even with $a_1(\text{quad}) = 0.0$, the acceptance is still small ($\sim 5 \text{ mm}$) indicating that the skew quadrupoles are not the factor that limits the acceptance. Consequently they were set to zero for all subsequent studies.

In the next study the effects of random errors in the dipoles were determined. Starting with all dipole errors included, acceptance determinations were made when multipoles of one order after another were set to zero. The acceptance was determined for the usual ten random number sequences when the following multipole orders were removed: 1, 1 to 2, 1 to 3, 1 to 4, and 1 to 5. The results appear in Fig. 2. Surprisingly the acceptance remains relatively unchanged even when all multipoles other than a_6 and b_6 were removed.

Pursuing the finding that the 14 pole (a_6 and b_6) multipole limited the acceptance to $\sim 5 \text{ mm}$, a study was made for which only one multipole order was nonzero. Again, if needed, the quadrupole strengths were readjusted to keep the tune at its nominal value. Determinations were made for the usual ten random number sequences, and the average value was used as the acceptance corresponding to the nonzero multipole. In addition, similar runs were made when the strengths of the multipole were reduced to 0.6 and 0.2 of the value used

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Fig. 1 Dependence of the acceptance on an rms rotational error of one mradian for all quadrupoles evaluated for ten different random number distributions.

for the RDS. An exception to this is found in the a_1 and b_1 multipoles. Since the value used for tracking in the RDS was 0.1 of the tabulated value, the strength of these multipoles was gradually increased until they were equal to the tabulated value. The acceptances resulting from these studies are plotted in Fig. 3. It seems that the higher order multipoles produce the major limitation to the acceptance.

The indication that the high order errors produce the major limitation to the acceptance led to another study in which successive orders of multipoles were set to zero--from the highest to the lowest. In this case acceptance determinations were made when the following orders were removed: 6, 5 to 6, 4 to 6, 3 to 6, and 2 to 6. These results are also plotted in Fig. 2 and indicate that the acceptance is limited as long as any multipole orders are present.

Fig. 2 Variation of the acceptance when random multipoles of particular orders are removed in all elements a). $a_n(d) = b_n(d) = 0.0$ for $n = 0, K$, b). $a_n(d), b_n(d) \neq 0$ for $n = 0, K$.

Fig. 3 Dependence of the acceptance on individual multipoles (a_n, b_n) as the strength is scaled by a factor f . For the RDS $f = 1.0$ for $2 \leq n \leq 6$, and $f = 0.1$ for $n = 1$.

The arithmetic scaling of multipole strengths shown in Fig. 3 indicates that a_6 and b_6 must be reduced by a factor of more than five before the acceptance increases significantly. In practice, all multipoles don't scale at the same rate; in fact, multipole coefficients a_n and b_n are expected to scale as $1/r^{(n+1)}$ as the radius of the magnet coil is changed. With $a_1(\text{quad}) = 0.0$ and the multipoles unchanged in all other elements, the multipoles in the crossing dipoles have been scaled as $1/r^{(n+1)}$ with r being the coil radius and n being the multipole order. A plan of the insertion near the crossing dipoles is included in Fig. 4. The acceptance of the lattice was determined for one random number sequence as the radii of the crossing dipoles BC1 and BC2 were increased. The tracking results show the acceptance to be nearly independent of the radius of BC2, but it is strongly dependent on the radius of BC1 where $\beta_y = 3383$ m. The dependence of the acceptance measured at the center of arc quadrupoles on the radii of BC1 and BC2 is plotted in Fig. 4. The dependence is pronounced with the acceptance increasing to nearly 12 mm (for this random number sequence) as the radius become large. The end points of Fig. 4 have been evaluated for all ten random number sequences and are plotted on Fig. 5. The magnitude of the effect of removing the random errors from the crossing dipoles varies from one random number sequence to another, but the average acceptance for all ten cases essentially doubles.

The indications that the first crossing dipole severely limits the acceptance of the entire machine is surprising when one considers that an aperture test of 1,000 mm is made in the insertions. The beam is not being lost in the insertion but in the arc where the aperture test is 15 mm. If the error fields in these dipoles have such a severe impact on the lattice, then they should also make invalid the method of determining the strengths of the Collins sextupoles used in the RDS. These strengths were determined by ignoring the effects of the multipole fields and determining $\Delta\alpha$, $\Delta\beta/\beta$, and $\Delta\psi = 2\pi\Delta v + \alpha/2$ by using the SYNCH program to track from the crossing point to both ends of the insertions. The sextupole strengths were adjusted to cancel these three quantities with no multipoles present. In case the multipoles are important, the method used to determine the sextupole strengths should be questionable--at best.

Conclusions

1). The rms rotational error assigned to the quadrupoles produces a limitation of the acceptance that is severe for some random number sequences. However, this error is not the one that limits the overall acceptance to ~ 5 mm in the RDS.

2). The limitation of the acceptance from higher order fields in the dipoles becomes more important as the multipole order increases.

3). The limitation of the acceptance appears to be due to the beam crossing points.

4). If these crossing dipoles are so important, then the method used to determine the strengths of the Collins sextupoles for the RDS was probably invalid in that the magnet errors could not be but were ignored when the strengths of these special sextupoles were determined.

Reference

1. Superconducting Super Collider, Reference Designs Study for U.S. Department of Energy, May 8, 1984.

Fig. 4 Dependence of the acceptance on the radius r of the beam crossing dipoles for a particular random number sequence (#1) when the associated multipoles were scaled as $(r/r_0)^{-(n+1)}$. Solid curve denotes BC1 and BC2, $\curvearrowright$ denotes BC1 only.

Fig. 5 Comparison of acceptances with $((r/r_0) = 1.0)$ and without $((r/r_0) = 0.0)$ random multipoles in the beam crossing dipoles for ten different random number sequences (indicated in each box).