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APERTURE STUDIES OF THE BNL COLLIDING BEAM ACCELERATOR
WITH REDUCED SUPERPERIODICITY*

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G.F. Dell

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DE84 002854

Brookhaven National Laboratory
Upton, New York 11973

Summary

Chromatic properties of the Brookhaven CBA (Colliding Beam Accelerator) with one low β insertion in each of the three superperiods have been studied using the PATRICIA particle tracking program. Systematic multipoles of order $5 < n \leq 10$ as well as random multipoles of order $1 \leq n \leq 10$ are, along with random closed orbit errors and sagitta effects, included when determining the aperture of the lattice.

1.0 Introduction

Aperture studies on the CBA have been made with the PATRICIA¹ particle tracking program. Results for the machine operated in the standard mode have been reported previously.² The present report documents changes in aperture that result for operation of the CBA in a mode having three low β insertions designed to produce luminosities in the $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ range.

The CBA lattice has 366 dipoles, 174 quadrupoles, and 540 multipole elements that are used to represent the higher order fields of the dipoles and quadrupoles. In addition, all dipoles in the 42 regular cells have either a focusing or defocusing chromaticity correcting sextupole at each end.

Separate sets of multipole coefficients are input for focusing quadrupoles, the defocusing quadrupoles, and the dipoles of the regular cells as well as for the dipoles and quadrupoles of the insertions. Each multipole set contains mean values as well as rms deviations for both normal and skew coefficients. The values of the multipole coefficients were obtained from the CBA Parameter List³. The average values of all multipoles of order $n \leq 5$ have been set to zero using the consideration that correction coils will be used to cancel the contributions of these multipoles.

For each magnet a set of normal and skew coefficients was generated according to a gaussian distribution that extends to three standard deviations on each side of the mean. The normal and skew coefficients were then combined to yield complex multipole coefficients used by PATRICIA.

Random closed orbit errors were generated according to a gaussian distribution whose modulus varied as $k\delta^{1/2}$. The rms values of the resulting errors were

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determined at the focusing and defocusing quadrupoles of the regular cells, and the factor k was adjusted to give an rms closed orbit error of 0.5 mm in the x and y directions at the focusing and defocusing quadrupoles, respectively. In the particle tracking the treatment of the closed orbit errors was limited to the extra kick associated with them.

2.0 CBA Aperture Scans

2.1 Standard Configuration

Aperture scans were made for the standard CBA having no low beta insertions at a working point of $\nu_x = 22.631$ and $\nu_y = 22.620$ with a chromaticity of 2.0 in both the x and y planes at $\Delta P/P = 0.0$ and with the requirement of a 2 percent momentum aperture at the injection energy of 30 GeV. The working line for the linear machine was determined for momentum deviations up to ± 1 percent. This working line was used as a reference for all subsequent aperture scans. An aperture scan was made for the CBA without multipoles. A second scan was made for which the influences of magnetic multipoles and closed orbit errors were included. For this scan the strengths of the quadrupoles in the regular cells were adjusted to bring the tunes at each $\Delta P/P$ back to the tunes of the reference working line.

At each $\Delta P/P$ particles having increasingly large x and y amplitudes and zero x' and y' were tracked. An emittance ratio of $\epsilon_y/\epsilon_x = 1.0$ was maintained as the amplitudes in the x and y directions were increased until a point was reached where the particle survived the requested number of turns at one amplitude but was lost within that number of turns at the next amplitude. Particles were tracked for 300 turns. A particle was considered lost when its amplitude $(x^2 + y^2)^{1/2}$ exceeded the machine aperture of 40 mm in any of the multipole elements.

The results of these scans are shown in Fig. 1. The bars on each point are used to signify that the particle survived the requested number of turns at the lower amplitude but was lost within that number of turns at the larger amplitude. The solid line denotes the expected physical aperture defined by beam size in the insertion quadrupoles for $-0.6 \leq \Delta P/P \leq 0.6$ percent and by dispersion in the regular cells for $|\Delta P/P| > 0.6$ percent. The aperture obtained by tracking without magnet multipoles and closed orbit errors agrees with the physical aperture derived from the machine functions. When the effects of magnet multipoles and closed orbit errors are included, the aperture is reduced by ~ 4.5 mm. The dashed line has been included to identify the data for the scan with multipoles.

2.2 Low β Configuration

To provide luminosities of $\sim 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, insertions have been designed with sets of dipoles between the crossing point and the first quadrupoles. These dipoles can be energized to reduce the crossing angle between the two beams, and

the insertion quadrupoles can be adjusted so that either the standard or low beta options are possible. One insertion capable of operating in either the standard or low beta mode is included in each of the three superperiods.

As before, aperture scans were made with and without multipoles. At each momentum the quadrupoles in the regular cells were adjusted to make the tune equal to that of the reference working line. The resulting aperture scans are shown in Fig. 2. As before, the solid line delineates the physical aperture obtained from the machine functions at each value of $\Delta P/P$. The reduced aperture results from the large beta functions in the quadrupoles nearest the crossing points as well as from the strong momentum dependence of these beta functions—see Fig. 3.

The aperture at $\Delta P/P = 0.0$ is reduced by a factor of ~ 1.7 for operation in the low beta mode. Since the aperture varies as $\epsilon^{-1/2}$, and ϵ varies inversely as the energy, the operation of the CBA in the low beta mode at ~ 95 GeV would give the same aperture as that of the standard CBA at 30 GeV. Hence injection into the normal CBA at 30 GeV and dynamic switching to the low beta mode at ~ 100 GeV is anticipated.

To assess the limitation to the aperture by the quadrupoles adjacent to the crossing points, scans were also made when the radial apertures of the first two quadrupoles on each side of the low beta crossing point were increased from 40 to

Fig. 1

Fig. 2

Fig. 1. Aperture scan for the CBA operated in the standard mode. A/A_0 is the relative amplitude with $A_0 = \epsilon_0 (\beta_x + \beta_y)^{1/2}$ and with $\epsilon_0 = 0.5\pi \cdot 10^{-6}$ radians, the nominal beam emittance. The upper curve denotes the aperture scan without multipoles; the lower curve denotes the aperture scan when multipoles and closed orbit errors are included.

Fig. 2. Aperture scan without (upper curve) and with (lower curve) multipoles for the CBA in the low beta mode of operation. The radial aperture of all machine elements is 40 mm.

Fig. 3

Fig. 3. Maximum values of β_x and β_y in the insertions for normal (CBA) and low beta (3LB) modes of operation.

Fig. 4

Fig. 4. Aperture scan without (upper curve) and with (lower curve) multipoles for the CBA in the low beta mode of operation when the radial aperture of the first two quadrupoles on each side of the crossing points is 50 mm.

50 mm. These results are shown in Fig. 4. In this case the low beta option has the same aperture at $\sqrt{s}$ 60 GeV that the standard CBA has at 30 GeV.

3.0 Aperture Reduction From Sagitta

The magnetic length of the CBA dipoles is 4.36 m, and the radius of curvature in these dipoles is 252.5 m. The sagitta in the dipoles is 9.8 mm; an additional 3.4 mm reduction results from the projection of the bore tube beyond the magnetic length of the dipole. The dipoles are positioned to divide this aperture reduction equally relative to the trajectory of an on momentum particle; the reduction is 6.6 mm.

At each multipole element a test is made to determine whether or not the particle has exceeded the radial aperture of the associated magnet. These multipole elements are located at the center of quadrupoles and at the downstream end of dipoles. The position of a particle is measured relative to an on momentum particle having zero amplitude rather than with respect to the centerline of the magnet. Since an on momentum particle makes an excursion of 6.6 mm on each side of the center line of a dipole, the effect of sagitta on reducing the physical aperture of a dipole has been treated by increasing $|x|$ by 6.6 mm when the test for aperture is made. Hence the condition for staying within the dipole aperture of 40 mm is:

Fig. 5(a)

Fig. 5(b)

Fig. 5(a). Aperture scan for the CBA without multipoles. Solid curve denotes aperture without sagitta; dashed curve denotes aperture when sagitta is included.

Fig. 5(b). Aperture scan for the CBA in the low beta mode of operation. Solid curve denotes the aperture scan without sagitta; dashed curve denotes the aperture scan when sagitta is included.

$$(|x| + 6.6)^2 + y^2 \leq 1600 \quad (1)$$

A partial aperture scan for the standard CBA was made for $|\Delta P/P| \geq 0.4$ percent, the region where the aperture is limited by dispersion in the regular cells. A significant reduction was observed and is shown in Fig. 5(a). In the CBA the aperture reduction due to bore tube projection in the dipoles nearest the horizontally focusing quadrupoles is reduced nearly a factor of two by rotating these dipoles ~ 1.5 mrad about their vertical axis. This correction has not been included in the present studies; consequently the reduction of aperture from sagitta and bore tube extension is approximately half that indicated in Figs. 5(a) and 5(b).

4.0 Conclusion

The present studies document the expected aperture when the CBA is operated in the low beta mode. To maintain the full aperture indicated in Fig. 1, injection at 30 GeV in the standard mode and switching at ~ 100 GeV to the low beta mode is anticipated. Increasing the radial aperture of the first two quadrupoles on each-side of the crossing point in the low beta insertion from 40 to 50 mm increases the aperture so that the low beta option could be used at an energy as low as 60 GeV. In Fig. 4 the expected aperture (solid curve) disagrees with the aperture obtained by tracking in the region $-0.8 < \Delta P/P < 0.0$ percent. This may

be an indication that the aperture is limited by the dynamic aperture rather than the physical aperture in this region; this point has not yet been investigated.

It should be noted that the quantity A/A_0 in all the aperture scans denotes the amplitude A relative to the amplitude A_0 that corresponds to the nominal beam emittance of $0.5\pi \cdot 10^{-6}$ m radians and that the CBA aperture is limited to $2.0\pi \cdot 10^{-6}$ m radians ($A/A_0 = 2.0$) by an injection septum. Hence, the aperture in the low beta mode without multipoles (Fig. 2) is almost adequate for operation at 30 GeV. Possible increases in aperture by reducing the strong momentum dependence of β_y (Fig. 3) by including extra families of sextupoles is being studied. Finally, aperture reduction from sagitta effects may become important at a $2\pi \cdot 10^{-6}$ m radian emittance for $|\Delta p/p| > 0.8$ percent.

References

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