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REDUCING β_x AND X_p BY THE USE OF A SPLIT QUADRUPOLE LATTICE

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MASTER

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ABSTRACT

The β_x function and the dispersion function X_p at the regular focusing quadrupole in the ISABELLE cell can be reduced by rearranging the quadrupoles and dipoles in the regular cell. In this arrangement, the focusing quadrupole is split in half and one or two of the dipoles in the cell are inserted between the two halves of the focusing quadrupole. This arrangement leads to a smaller beam size, and can sometimes lead to a smaller aperture requirement.

I. Introduction

During the conceptual study of a lattice suited for a 300 GeV ISABELLE, it was concluded that a cell with 5 dipoles, each 4.20 m long, leads to a satisfactory solution. Retaining a symmetrical cell structure is then possible by splitting the focusing quadrupole; the cell structure becomes FOFODO. Although one more quadrupole unit per cell (when compared with the simple FODO structure) represents an economic penalty, it was observed that the split-quadrupole lattice has smaller peak values of the β_x and X_p functions. It, therefore, seemed indicated also to investigate the implications of the split quadrupole configuration for the 400 GeV lattice.

In this report we discuss quantitatively the reduction of the β_x function and the horizontal dispersion at the regular focusing quadrupole in the 400 GeV ISABELLE which would result from the use of a split quadrupole lattice. This reduction in β_x and X_p translates into a smaller size of the stack and the injected beam at the place where they are largest. For the 400 GeV ISABELLE, the beam size is reduced from 56 mm to 48 mm, a reduction of 8 mm. Beam size here means the horizontal extent of the stacked beam plus the injected beam plus the required space between them as measured at the center of the focusing quadrupoles, QF. The effect on aperture requirements is discussed below.

II. β_x, X_p Comparison

Figure 1a shows the present configuration of the regular cell for the 400 GeV ISABELLE, in which the focusing quadrupole QF is separated from the divergent quadrupole QD by three 4-3/4 meter dipoles. In Fig. 1b, the focusing quadrupole QF is split in half

1. ISABELLE Division Staff, BNL Report 50656 (ISA 77-5), 1977.

Fig. 1

and two of the dipoles are inserted between the two half quadrupoles QFH. The arrangement shown in Fig. 1b can be considered as approaching the case of a combined function lattice thus leading to lower values of β_x and also X_p .

Figure 2 shows the results of computer calculations using the SYNCH program for the β_x and X_p through the normal cell for the present ISABELLE lattice, with the quadrupole QF not split and for the split quadrupole lattice shown in Fig. 1b. The gradient has been adjusted so that both lattices have the same phase shift per cell of 94° horizontally and 79° vertically. One sees that the maximum β_x is reduced from 63.8 to 43.5 m, a reduction of 32%, and the maximum X_p is reduced from 2.49 to 2.12 m, a reduction of 15%.

If the quadrupole gradient is held constant for both lattices at $G = 6.70$ kG/m, it was found that the length of a full quadrupole had to be increased by about 20%, from 1.44 m to 1.75 m. Also, the maximum β_y was found to increase by 19%, from 68 m to 81 m.

A combined function lattice was also studied. This lattice consists of 6 combined function dipoles, each $4\frac{3}{4}$ meters long. Three dipoles had positive gradients and were followed by three dipoles having negative gradients. For this lattice, the maximum β_x is 46.2 m and the maximum X_p is 1.9 m. These results are not too different from the results found for the split quadrupole lattice above.

III. Beam Size

Figure 3 shows the variation of the beam size, ΔX_b along the normal cell for the present ISABELLE lattice, and for the split quadrupole lattice. The maximum beam size is reduced from 56 mm for the present ISABELLE lattice to 48 mm for the split quadrupole lattice, a reduction of 8 mm or 14%.

Fig. 2

Fig. 3

IV. Aperture Requirements

In order to compare the aperture requirements for the two lattices, let us assume that the beam moves inside a circular vacuum chamber of 80 mm diameter. In addition, the beam is limited by a dump profile. The transverse position of the dump profile varies with the azimuthal position. If a detector is put at the horizontal position χ_d at one azimuth, it will detect particles which at other azimuths are further or closer than χ_d depending on the local value of β_x and X_p . The horizontal position of a particle relative to the $\Delta p/p = 0$ orbit varies roughly as $\sqrt{\beta_x}$ through the regular cell, since the horizontal position depends on its betatron oscillation amplitude which dependence goes like $\sqrt{\beta_x}$ and also depends on its energy $\Delta p/p$ which dependence also goes roughly like $\sqrt{\beta_x}$ since X_p varies roughly as $\sqrt{\beta_x}$ in the regular cell. Thus, the position of the dump profile through the regular cell obeys

$$\chi_d - |\chi_s| = \text{const.} \sqrt{\beta_x}, \quad (4.1)$$

where χ_d is the position of the dump profile relative to the central axis of the vacuum chamber, and χ_s is the sagitta or the position of the central orbit relative to the vacuum chamber axis. Equation (4.1) together with the restriction that the dump profile not be closer than 3 mm to the vacuum chamber wall determines the dump profile around the machine.

The clearance space, χ_c , between the horizontal edge of the beam and the dump profile can be used as a measure of the available aperture. χ_c is given by

$$\chi_c = \chi_d - |\chi_s| - \Delta\chi_b/2, \quad (4.2)$$

where $\Delta\chi_b$ is the horizontal beam size. $\Delta\chi_b$ varies like $\sqrt{\beta_x}$ through the regular cell since X_p varies roughly as $\sqrt{\beta_x}$, and the clearance space will roughly vary through the cell as $\sqrt{\beta_x}$. The smaller clearance space at a point where β_x is smaller is not less effective

because the closed orbit errors are also smaller there by the same factor $\sqrt{\beta_x}$. One can introduce an effective clearance space

$$\chi_{c,ef} = \sqrt{\frac{64}{\beta_x}} \chi_c, \quad (4.3)$$

where 64 is the largest β_x for the FODO lattice. $\chi_{c,ef}$ is roughly constant through the regular cell, and gives an indication of the effectiveness of the clearance space, and can be used to make comparisons of the aperture available for different situations.

For a curved vacuum chamber which follows the central orbit in the dipoles, $\chi_s = 0$ through the cell. The dump profile and the clearance space is given in Table I for the two lattices at the 4 most severe locations where the beam comes closest to the dump profile. For the FODO lattice, results are given at the locations QF which is at the center of the focusing quadrupole, and B_1 , B_2 , B_3 which are the entering edge, center, and exit edge of the following dipole. For the split quadrupole lattice, results are given at B_1 , B_2 , B_3 , which are the entering edge, center and exit edge of the second dipole between the split quadrupole, and at QFH, which is at the center of the following split quadrupole. The effective clearance space is $\chi_{c,ef} = 8.8$ mm for the FODO lattice and $\chi_{c,ef} = 14.9$ mm for the split quadrupole lattice.

Table I. Clearance space and dump profile for the case of a curved vacuum chamber.

		Location	β_x (m)	$\Delta\chi_b/2$ (mm)	χ_d (mm)	χ_c (mm)	$\chi_{c,ef}$ (mm)
FODO Lattice		QF	64	28	37	9	9.0
		B_1	59.5	27	35.6	8.6	8.9
		B_2	48	24.2	32	7.8	9.0
		B_3	37	21.4	28.1	6.7	8.8
Split Quad Lattice		B_1	42.7	24.1	37	12.9	15.5
		B_2	43	24.3	37	12.7	15.2
		B_3	43.2	24.4	37	12.6	15.1
		QFH	43.6	24.6	37	12.4	14.9

For a straight vacuum chamber, the beam central orbit departs from the axis of the vacuum chamber and has a maximum sagitta of ± 6.3 mm. The ± 6.3 mm includes the effect due to the vacuum chamber extending past the dipole, at both ends, by 30 cm past the effective dipole length of 4.63 m. The dump profile and the clearance space for this case is given in Table II. Because of the sagitta, the dump profile comes closest to the wall at the edge of the dipole near the focusing quadrupole, and the dump profile in the quadrupole is at 31.9 mm for the FODO lattice and at 30.7 mm for the split quadrupole lattice. The effective clearance space is 3.9 mm for the FODO lattice, and 7.4 mm for the split quadrupole lattice.

The discussion assumes implicitly that the physical vacuum chamber aperture is equal in all magnets. In elements where the difference between physical aperture and dump profile exceeds the minimum tolerable value (taken as 3 mm on the radius) one has the situation of excess aperture and, in principle, the physical aperture could here be reduced.

Table II. Clearance space and dump profile for case of a straight vacuum chamber

	Location	β_x (m)	$\Delta x_b/2$ (mm)	x_d (mm)	x_s (mm)	x_c (mm)	$x_{c,ef}$ (mm)
FODO Lattice	QF	64	28	31.9	0	3.9	3.9
	B ₁	59.5	27	37	-6.3	3.7	3.9
	B ₂	48	24.2	33.9	6.3	3.4	3.9
	B ₃	37	21.4	30.6	-6.3	2.9	3.9
Split Quad Lattice	B ₁	42.7	24.1	36.5	-6.3	6.1	7.5
	B ₂	43	24.3	36.8	6.3	6.2	7.4
	B ₃	43.2	24.4	37	-6.3	6.3	7.4
	QFH	43.6	24.6	30.7	0	6.1	7.4

It has been suggested by A. van Steenberghe that the clearance space for the FODO lattice with a straight vacuum chamber can be improved by either rotating the dipole near the focusing quadrupole, or by flaring the vacuum chamber at the edge of this dipole which is closest to the quadrupoles. These results are given in Table III for a rotation of the dipole that moves the ends of the dipole by ± 3.4 mm, and for flaring the vacuum chamber at the dipole edge

nearest to the focusing quadrupole by 6.4 mm. In the flared case, the dipole is also moved outward by $\Delta\chi = 1.3$ mm. By rotation of the dipole, one obtains an effective clearance space $\chi_{c,ef} = 7.3$ which is almost the same as that obtained with the split quadrupole lattice. By flaring the vacuum chamber by 6.4 mm, one obtains $\chi_{c,ef} = 8.8$ mm.

Table III. Clearance space and dump profile when a straight vacuum chamber is rotated or flared.

	Location	β_x (m)	$\Delta\chi_b/2$ (mm)	χ_d (mm)	χ_s (mm)	χ_c (mm)	$\chi_{c,ef}$ (mm)
	QF	64	28	35.5	0	7.5	7.5
FODO	B_1	59.5	27	37	-2.9	7.1	7.5
Rotation	B_2	48	24.2	37	6.3	6.5	7.5
± 3.4 mm	B_3	37	21.4	36.6	-9.7	5.5	7.3
	QF	64	28	37	0	9	9
FODO	B_1	59.5	27	43.4	-7.6	8.8	9.2
6.4 mm Flare	B_2	48	24.2	37	5.0	7.8	9.0
$\Delta\chi = 1.3$ mm	B_3	37	21.4	35.7	-7.6	6.7	8.8
	B_1	42.7	24.1	43	-9.3	9.6	11.5
Split Quad	B_2	43	24.3	37	3.3	9.4	11.3
6 mm Flare	B_3	43.2	24.4	43	-9.3	9.3	11.2
$\Delta\chi = 3$ mm	QFH	43.6	24.6	34	0	9.4	11.3

In the case of the split quadrupole, one does not gain by rotating the dipole. Because the dump profile does not change much from the B_1 to the B_2 points in the dipole, nothing can be gained by rotation. However, by flaring the vacuum chamber by 6 mm at both ends of the dipoles between the focusing quadrupoles, and moving these dipoles 3 mm outwards, one obtains $\chi_{c,ef} = 11.2$ mm. The dipoles just outside the focusing quadrupoles have to be rotated by about ± 2 mm. The results for the flared case are given in Table III.

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