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CORRECTION OF SYSTEMATIC DIPOLE ERRORS WITH 90 METER HALF-CELLS

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ABSTRACT

Compensation of systematic dipole errors with the new, shorter, 90 m half-cells and the new, higher, 2 TeV injection energy is investigated. Compensation is greatly simplified compared to the previous situation. In that case it was known that either bore-tube or various lumped correction schemes, such as Simpson-Neuffer or Gaussian, were satisfactory. Such sophisticated correction schemes are no longer needed. Having a correction element in each half-cell interior, though no longer strictly necessary, does permit compensation many times better than specifications; the exact position in the interior is not critical. Nonlinear systematic multipoles that certainly require compensation are b_2 and b_4. Accuracy of this compensation does not favor either of the two configurations tested, five or six dipoles per half-cell, relative to the other. The preceding statements apply to dipoles with bore diameter of 4 cm. Compensation of dipoles with 5 cm bore is also studied and shown to be still more accurate. Determination of the need for compensation of the "unallowed" b_3 depends upon presently unavailable input data.

This can be regarded as an addendum to the report SSC-SR-1038, *Compensation of SSC Lattice Optics in the Presence of Dipole Field Errors.* It gives the large amplitude tunes in the new, shortened, 90 meter cells. The tables have the same format as in that report. The main convention about the entries is that they are tune shifts, away from small-amplitude, on-momentum, tunes measured in units of 0.001. In these units, 10 marks the boundary between "good" and "bad". More precisely, at standard "large" amplitudes of 5 mm (3.6 mm off-momentum) the difference between the most positive and the most negative entry was specified to not exceed 10 units. For more detail refer to SSC-SR-1038. Systematic multipoles, appropriate for 2 TeV injection, with 4 cm and 5 cm bore diameters are taken from Table D.2 (p. 84) of that report. For 4 cm, in the standard units, they are $b_2 = -3.0, b_3 = 0.1, b_4 = 0.20, b_6 = -0.05$. For 5 cm, they are $b_2 = -1.9, b_3 = 0.1, b_4 = 0.09, b_6 = -0.017$.

All results in SSC-SR-1038 are appropriate for 1 TeV injection into a collider having cells of length 115 m. The effect of going to the new, more conservative parameters can be inferred by comparison with numbers in that report. Briefly, it can be stated that tune variations have been reduced by a factor of two or three or more, in corresponding cases. In one case below a table will be transcribed from that report for such a comparison. This reduction reflects itself in a simpler compensation scheme being required. For example, it appears possible to avoid lumped correctors interior to half-cells, at least if the acceptability criteria of the previous report are retained.

The same standard amplitudes are analysed as in the previous report. In effect, this makes the acceptability criteria more conservative because it does not take advantage of any reduction in the "needed aperture" accompanying the reduced beta-functions and the increased injection energy. Another comment, in the same spirit, applies to both the previous and the present report. The acceptability criteria are applied to very large position and energy offsets from the central values; they will be required only during injection. During colliding beam operation, when very small tune spreads will be required, the amplitudes

required will be less by factors of at least three. Since the dependences being compensated are quadratic or higher powers of amplitude, much tighter tune control will be possible during colliding beam operation.

Results with 4 cm bore are presented first. From the first table it can be seen that having no correction at all is unacceptable, but that distributed (bore-tube) compensation of b_2, with no further correction, is almost acceptable.

90 METER CELLS, 4 CM BORE										
NO LUMPED CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
Uncorrected	ΔQ_x	4.0	3.8	3.8	9.3	-12.0	-14.6	15.9	-4.8	3.5
	ΔQ_y	-2.9	-1.6	-1.9	-11.1	7.7	5.8	-15.0	4.2	-3.8
Bore-tube b_2	ΔQ_x	0.2	1.1	0.1	-4.7	-0.5	-7.0	-11.4	-4.2	-11.7
correction only	ΔQ_y	0.3	-0.6	-1.6	-0.7	-5.0	-6.9	-0.2	-3.5	-4.4

Two lumped-correction schemes are known from the previous report to give adequate compensation; in the present, more conservative, lattice this is necessarily even more true. The schemes are "Simpson-Neuffer" if there are 6 dipole units per half-cell, and "Gaussian" if there are 5. Both require correctors in mid-cell locations. Gaussian gives somewhat better compensation and is free of end effects; Simpson-Neuffer permits somewhat weaker steering elements if the steering elements and correction elements are in the same packet—which is convenient.

The next two tables show, with either of the two sophisticated lumped schemes, Simpson-Neuffer or Gaussian, that lumped compensation of b_2, b_3 and b_4 gives glorious, ten times better than specs, compensation. This does not depend

on b_6 compensation but leaving out the b_4 compensation reduces it to marginal acceptability.

90 METER CELLS, 4 CM BORE										
SIMPSON-NEUFFER CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
b_2, b_3, b_4, b_6	ΔQ_x	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1
	ΔQ_y	0.5	0.5	0.5	0.4	0.5	0.4	0.5	0.5	0.5
b_2, b_3, b_4 only	ΔQ_x	0.3	0.2	0.2	0.2	0.1	0.1	0.0	0.1	0.1
	ΔQ_y	0.3	0.5	0.5	0.4	0.5	0.4	0.6	0.5	0.5
b_2, b_3 only	ΔQ_x	-6.8	4.0	-3.4	0.2	0.1	0.2	7.0	-3.8	0.2
	ΔQ_y	7.2	-2.9	4.5	0.4	0.5	0.5	-6.9	2.7	-2.8
b_2 only	ΔQ_x	3.2	3.6	2.5	8.0	-11.9	-15.2	15.6	-5.6	1.3
	ΔQ_y	-2.9	-1.6	-1.6	-11.0	8.0	5.1	-15.0	4.2	-3.6
GAUSSIAN CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
b_2, b_3, b_4, b_6	ΔQ_x	0.2	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0
	ΔQ_y	0.4	0.5	0.5	0.4	0.5	0.3	0.4	0.5	0.3
b_2, b_3, b_4 only	ΔQ_x	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
	ΔQ_y	0.2	0.5	0.4	0.2	0.5	0.3	0.5	0.5	0.4
b_2, b_3 only	ΔQ_x	-6.8	3.9	-3.5	0.1	0.0	0.1	6.6	-3.8	0.2
	ΔQ_y	6.5	-3.0	4.4	0.3	0.5	0.3	-6.9	2.4	-2.9
b_2 only	ΔQ_x	3.0	3.4	2.0	8.0	-12.0	-15.3	15.4	-6.0	1.0
	ΔQ_y	-3.0	-1.6	-1.7	-11.6	7.9	5.0	-15.0	4.2	-3.6

It should be remembered that all kinds of effects not being included in the present analysis cause tune shifts at the "10 unit" level; for that reason it is somewhat of an empty accomplishment to achieve compensation at the "1 unit" level, as has been accomplished here. In any case, compensation at the "10 unit" level can be accomplished using "remote" or even "global" compensation. This has been studied in SSC-SR-1038.

With the 115 m half-cell length and 1 GeV injection energy, it was known to be impossible to obtain adequate compensation with steering elements restricted to spool-piece locations beside the quads. With the present lattice, this question can be re-opened.

The next table deals with the possibility of restricting lumped correctors in this way. It shows that the acceptability criteria barely miss being met, using only lumped correctors at the spool-piece locations beside the quadrupoles. Correctors required are b_2, b_3 and b_4. The corrector strengths are adjusted simply to remove the field integral of each particular multipole, integrated around the ring, without reference to the beta-function values at the correction element positions.

With the correction elements wired in families, it is still possible to change the family strengths empirically, rather than to cancel the field integral, as was done in the previous table. The next table shows the results after empirically optimizing the settings of the lumped b_3 and b_4 coils that are located in the spool-pieces. In both cases shown the b_2 strengths are set to cancel the chromaticities. In the first case, this b_2 compensation is with bore-tube coils; in the second, it is with lumped elements in the spool-pieces. It can be seen that the specifications are met.

90 METER CELLS, 4 CM BORE										
SPOOL-PIECE ONLY CORRECTION, 4 cm bore.										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
b_2, b_3, b_4, b_6	ΔQ_x	1.1	-0.3	0.8	-3.7	-4.1	-4.1	-9.9	-3.9	-11.3
	ΔQ_y	0.4	-0.2	-0.9	-0.9	-6.8	-6.8	-0.1	-3.4	-4.1
b_2, b_3, b_4 only	ΔQ_x	3.1	-0.3	1.1	-3.7	-0.5	-4.1	-11.1	-3.9	-11.5
	ΔQ_y	0.1	-0.4	-1.6	-0.9	-4.5	-6.8	0.3	-3.4	-3.8
b_2, b_3 only	ΔQ_x	-10.9	0.5	-7.9	-3.7	-0.5	-4.1	2.6	-7.3	-3.9
	ΔQ_y	7.2	-4.3	1.4	-0.8	-4.8	-6.9	-7.1	0.5	-5.9
b_2 only	ΔQ_x	4.0	3.8	3.8	9.2	-12.0	-14.7	15.9	-4.9	3.4
	ΔQ_y	-2.9	-1.3	-1.7	-11.1	7.9	5.9	-15.0	4.2	-3.7

2 TeV INJECTION, 90 m HALF-CELLS, OPTIMIZED SPOOL FITTING										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
Bore-tube b_2	ΔQ_x	0.5	0.6	0.4	0.7	-4.9	-7.0	1.6	-4.3	-5.2
Spool b_3, b_4 fit	ΔQ_y	-0.2	-2.7	-3.0	-6.4	-3.4	0.8	-6.9	-4.1	0.6
Chrom. b_2 fit	ΔQ_x	3.2	3.3	0.9	3.6	-3.8	-6.1	3.8	-3.8	-4.6
Spool b_3, b_4 fit	ΔQ_y	0.0	-2.6	-2.8	-6.7	-3.4	0.9	-7.7	-4.1	0.7

The last entries in the previous table can be compared with those in the next table, copied from SSC-SR-1038 (p. 34). It shows that the large amplitude behavior is not better in the shortened cell, but that the off-momentum compensation is several times more accurate.

1 TeV INJECTION, 115 m HALF-CELLS, OPTIMIZED SPOOL FITTING											
δ		-0.001			0.0			0.001			
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
Chrom. b_2 fit	ΔQ_x	8.1	17.3	12.2	-2.7	-5.0	-3.7	-15.6	-27.8	-17.0
Spool b_3, b_4 fit	ΔQ_y	12.5	11.7	0.6	-3.3	-7.1	-3.4	-19.6	-22.5	-7.6

From these successes at compensation it can be seen that shortening the cell length and increasing the injection energy has eliminated the need for sophisticated schemes. It continues to be true that compensation to levels many times better than the specs is possible, but it requires elements in the interiors of half-cells.

Obviously the sensitivity has been reduced to levels such that neither the Simpson-Neuffer nor Gaussian schemes needs to be followed religiously. The data in the next table investigates this statement. A "Displaced Gaussian" lumped configuration is tested in which the Gaussian correctors are displaced by one magnet, so that one corrector is in the convenient spool-piece location. That is, instead of appearing at locations 1-2 and 4-5 within the half-cell, they appear at locations 0-1 and 3-4. (The notation 1-2 indicates the drift space between magnet 1 and magnet 2, and so on.) Otherwise they have equal strengths, the same as for Gaussian, dead-reckoned to cancel the integrated systematic multipole. This could also be thought of as a modification of the Simpson-Neuffer scheme, with the "center" corrector somewhat off-center. This suggests that the optimal

weighting of strengths would be between the 1:2 of Simpson-Neuffer and the 1:1 of Gaussian. The results in the table show that the specifications are met by a factor of 4, even without bothering to optimize this ratio. Cursory efforts to improve the compensation further by adjusting this ratio gave no improvement.

DISPLACED GAUSSIAN											
δ		-0.001			0.0			0.001			
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
Chrom. b_2 fit	ΔQ_x	0.2	0.1	0.2	-0.1	0.0	-0.5	-1.7	-0.3	-2.6
$b_3, b_4 \equiv$ Gaussian	ΔQ_y	0.4	0.4	0.2	0.1	-0.6	-2.1	0.3	-0.1	-0.6

From these results one concludes that the decision as to the number of dipoles per half-cell can be made on the basis of cost and/or convenience, without reference to the issue of compensation.

The remaining tables repeat many of the previous conditions except for the change of using systematic errors appropriate to a bore diameter of 5 cm. The compensation is somewhat better than with 4 cm bore; typically 30 percent or so.

90 METER CELLS, 5 CM BORE										
NO LUMPED CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
Uncorrected	ΔQ_x	6.9	0.3	3.5	8.3	-12.4	-15.4	11.9	-3.6	3.2
	ΔQ_y	-6.6	0.3	-3.3	-11.1	6.3	4.9	-11.2	1.2	-4.1
Bore-tube b_2	ΔQ_x	0.8	-0.3	0.0	0.7	-7.0	-5.0	1.1	-3.7	-3.5
correction	ΔQ_y	-3.3	-0.6	-3.2	-6.7	0.9	-3.4	-6.8	0.1	-4.0

SIMPSON-NEUFFER CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
b_2, b_3, b_4, b_6	ΔQ_x	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	ΔQ_y	0.4	0.4	0.3	0.4	0.4	0.3	0.5	0.5	0.4
b_2, b_3, b_4 only	ΔQ_x	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	ΔQ_y	0.4	0.5	0.4	0.4	0.4	0.3	0.5	0.5	0.5
b_2, b_3 only	ΔQ_x	-3.5	0.9	-0.2	0.1	0.1	0.1	3.5	-2.1	0.1
	ΔQ_y	3.5	-0.6	1.0	0.4	0.4	0.4	-3.2	0.8	-1.1
b_2 only	ΔQ_x	5.4	0.3	3.0	8.0	-12.0	-15.4	11.8	-3.6	2.4
	ΔQ_y	-6.5	0.4	-3.2	-11.0	7.8	4.8	-11.2	1.5	-3.7

90 METER CELLS, 5 CM BORE										
SPOOL-PIECE ONLY CORRECTION										
δ		-0.001			0.0			0.001		
		3.6,0	3.6,3.6	0,3.6	5.0,0	5.0,5.0	0,5.0	3.6,0	3.6,3.6	0,3.6
b_2, b_3, b_4, b_6	ΔQ_x	2.1	-0.2	0.2	2.4	-7.2	-4.3	2.7	-3.7	-3.1
	ΔQ_y	-3.3	-1.0	-3.3	-6.8	0.7	-3.7	-6.8	-0.1	-4.5
b_2, b_3, b_4 only	ΔQ_x	2.5	-0.2	0.1	2.4	-7.2	-4.3	2.3	-3.7	-3.1
	ΔQ_y	-3.3	-1.0	-3.3	-6.8	0.7	-3.7	-6.8	-0.1	-4.4
b_2, b_3 only	ΔQ_x	-0.1	0.0	-0.9	2.4	-7.2	-4.3	4.4	-3.8	-0.5
	ΔQ_y	-2.5	-2.8	-3.2	-6.8	0.7	-3.7	-7.3	0.5	-4.5
b_2 only	ΔQ_x	6.9	0.3	3.4	8.3	-12.4	-15.4	11.9	-3.6	3.2
	ΔQ_y	-6.6	0.3	-3.3	-11.1	6.3	4.8	-11.2	1.2	-4.1