Magnetic Correction of RHIC Triplets

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I INTRODUCTION

Triplets of large bore quadrupoles will be antisymmetrically placed on either side of all six intersection points of the Relativistic Heavy Ion Collider (RHIC) [1]. In RHIC collision optics, the triplets at the two experimental detectors are intended to enable the collision beta function to be reduced to the design goal of $\beta^* = 1.0$ meter in both planes, in order to minimize the spot size and maximize the luminosity. This requires running with $\beta_{max} \approx 1400$ meters in the triplet, where the beams will have their largest size, both absolutely and as a fraction of the available aperture. Hence, the ultimate performance of RHIC rests on achieving the highest possible magnetic field quality in the triplets.

Figure 1 shows the layout of a triplet, with the quadrupoles moved as close together as possible. Table 1 lists some triplet parameters, such as the different lengths of quadrupoles Q1, Q2, and Q3, and the 5σ beam size - about 71% of the 6.5 cm coil radius. All three quadrupole models have the same coil and iron cross-section in the main body, and all have the same coil "saddle" ends and electrical lead geometry. Lumped correctors, labeled C1, C2, and C3 in the Figure, carry three nonlinear windings to compensate for measured multipoles, in addition to carrying dipole corrector windings. This paper discusses the correction of magnetic errors expected in the quadrupole bodies and ends, using both these lumped correctors and also quadrupole body tuning shims.

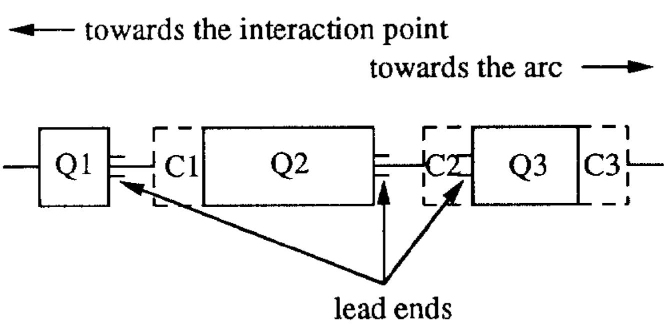

Figure 1 Schematic layout of the RHIC triplet, showing the quadrupoles, the orientation of the quadrupole lead ends, and the local correctors C1, C2, and C3 .

*Operated by Associated Universities Incorporated, under contract with the U.S. Department of Energy.

Number of triplet quads in RHIC	72	
Magnetic length of Q1, Q2, Q3	1.44, 3.40, 2.10	[m]
Operating temperature	4.35	[K]
Design gradient	48.1	[T/m]
Design current	5.0	[kA]
Maximum triplet beta function	1.40	[km]
Maximum transverse beam size (5σ)	0.047	[m]
Coil inner diameter	0.130	[m]
Coil outer diameter	0.154	[m]
Iron inner diameter at midplane	0.174	[m]
Iron inner diameter at pole	0.184	[m]
Iron outer diameter	0.350	[m]
Minimum beam spacing at Q1	0.424	[m]

Table 1 Some basic triplet design parameters

II QUADRUPOLE BODY AND END HARMONICS

A detailed description of the triplet quadrupole design and construction can be found elsewhere [2,3]. To summarize, design or construction errors in the placement of the single layer coil are the strongest potential source of unwanted field harmonics. These harmonics are independent of excitation. By contrast, error harmonics generated from mislocation of the iron yoke are weaker - but still dangerous - and depend on the excitation level because of saturation effects. Almost negligible is the weak magnetic coupling of side-by-side triplets in RHIC's two horizontally separated rings. Two Q1 magnets lie in a common cryostat because the reference orbits are not fully separated this close to the intersection point.

All harmonics are optimized at 5,000 Amps, the maximum operating current, and so careful attention has been paid to locations in the yoke where the iron tends to saturate. In particular, the inner surface of the yoke makes a smooth transition from an arc of radius 87 mm to an arc of radius 92 mm. The angle that this transition makes with the midplane, and the corresponding transition angle of the RX630 plastic spacer that separates the coil and the yoke, are slightly different. This leaves eight symmetrically placed 7 millimeter holes between the spacer and the iron, where composite tuning shims will be installed. The nominal mix of 50% iron, 50% brass, will be varied for field harmonic correction.

Table 2 shows the tentatively expected values for the mean and standard deviation of normal and skew quadrupole harmonics, b_n and a_n, in triplet quadrupoles. Only significant harmonics with absolute systematic or random values greater than 0.1 are listed. The mean or "systematic" values are based on measurements of two prototype

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quadrupoles, reported elsewhere [3,4], but they have been modified to reflect the predicted effect of a modest design iteration on future magnets. This iteration will remove most of the differences between predictions and measurements in the prototypes, so that the allowed multipoles b_5, b_9 and b_{13} come closer to zero. Random errors in the Table come from the copious measurements of 8 cm aperture RHIC arc quadrupoles. The standard notation used is defined by

$$(B_y + iB_x) = G(x + iy) \cdot \left(1 + 10^{-4} \sum_n (b_n + ia_n) \left(\frac{x+iy}{R}\right)^{n-1}\right) \quad (1)$$

where G is the nominal gradient in the center of the quadrupole body, and $R = 4.0625$ cm is the reference radius.

ORDER, n	NORMAL		SKEW	
BODY	$\langle b_n \rangle$	$\sigma(b_n)$	$\langle a_n \rangle$	$\sigma(a_n)$
1		10.0	.8	.4
2	.5	1.4	.1	1.2
3	(.0)	.6	.3	.7
4	.3	.6	.1	.5
5	1.5	.5	-.4	.1
9	-.2	.1	.0	.1
LEAD END	$\langle B_n \rangle$	$\sigma(B_n)$	$\langle A_n \rangle$	$\sigma(A_n)$
1			5.6	2.4
2	-.1	.7	-2.5	1.1
3	-.3	.3	.4	.1
5	2.8	.3	-1.6	.2
9	.3	< .1	.2	< .1
RETURN END	$\langle B_n \rangle$	$\sigma(B_n)$	$\langle A_n \rangle$	$\sigma(A_n)$
1			-.4	.4
2	.3	1.8	1.4	.5
3	-.1	.2	-.1	.3
4	.0	.1	.2	.2
5	1.4	< .1	-.1	< .1

Table 2. Expected mean and standard deviation for triplet quadrupole harmonics at 5,000 Amps, derived from prototype magnet measurements plus a minor design iteration.

The four quadrupole coils are electrically interconnected at the "lead end" of the quadrupole, by carrying two leads from each coil beyond the body of the magnet to a splice plate. These eight leads generate allowed field harmonics - b_1, b_5, b_9, .. and a_1, a_5, a_9 .. - both inside and outside the iron. The leads go through a 90^0 rotation once they are out of the magnet, effectively changing the sign of the current in the lead, and the sign of the multipoles generated. Each coil is also bent around a saddle at both the lead end and the "return end" of its pole piece. These saddles are designed to give near zero allowed harmonics b_5 and b_9. Table 2 also lists the expected *integrated* quadrupole end harmonics, B_n and A_n, where, for example,

$$B_n \equiv \int_{end} b_n \, dl \quad (2)$$

Body and end harmonics in Table 2 may be directly compared after multiplying the body value with the magnetic length of the appropriate quadrupole. This shows that only the b_5 (dodecapole) end harmonics are of real concern.

Triplet quadrupoles are measured with the lead end away from an observer who is looking along the s-axis, through the magnet. The x-axis points to the left, and the y-axis points vertically upwards, in a right handed (x,y,s) measurement coordinate system. Table 3 indicates how to get from the sign of a measured harmonic to the sign of the actual harmonic, when a magnet has been rotated about a vertical axis between measurement and installation, so that the lead end is nearest the observer. Note that the sign of a harmonic is independent of the polarity of the magnet power supply.

dipoles:	$b_n \rightarrow (-1)^n \, b_n$,	$a_n \rightarrow (-1)^{n+1} \, a_n$
quads:	$b_n \rightarrow (-1)^{n+1} \, b_n$,	$a_n \rightarrow (-1)^n \, a_n$

Table 3 After rotating by 180 degrees about the vertical axis.

III TRIPLET CORRECTION STRATEGY

The nominal horizontal and vertical tunes, 28.190 and 29.180, lie between 5th and 6th order resonances. Tune shifts from all contributions must be kept well below 0.033 in order for the beam to remain well within the tune plane triangle defined by these resonances and the coupling diagonal. The triplet errors shown in Table 2 dominate the tune shift contribution at storage - with two interaction regions operating at $\beta^* = 1$ m and four at $\beta^* = 10$ m - if they are uncorrected by shimming or by local correctors.

ORDER, n	NORMAL, b_n	SKEW, a_n
0	C1 or C3	C3 or C1
1	-	C2
2	S, (C2)	S
3	S, C1, C3	S, (C2)
4	S, C1, C3	S
5	S, C1, C3	S, (C2)
6+	-	-

Table 4 The triplet quadrupole correction strategy.

Table 4 shows which correction methods will be used for each harmonic - 'S' indicates that a multipole is corrected by shimming, while 'C1' indicates, for example, that a winding in local corrector C1 is independently powered. An entry in parentheses means that a winding is present on a contingency basis - a power supply is not expected to be connected to it. Live correction might also be possible, by adjusting the lumped corrector excitations according to operational beam dynamics measurements. This is not proposed here, however, since this is not a conventional procedure at existing colliders.

The nominal thickness of the iron part of a tuning shim is 3.3 mm, but this can vary from 0.0 to 6.6 mm, easily sufficient to correct for the expected harmonics. After magnetic measurements on an individual magnet, the shim vector representing the 8 thicknesses is found [5] such that

$$\int_{\text{body}} (b_n + Db_n)\, dl \;+\; B_{n\ \text{lead}} \;+\; B_{n\ \text{return}} \;=\; 0 \qquad (3)$$

for the 8 goal harmonics, n = 2 through 5, normal and skew. Unfortunately the shims also cause feed up and feed down harmonics. Feed down to orders 0 and 1 is unimportant, since these harmonics are readily compensated by dipole and quadrupole correctors. Most prominent is feed up to b_9, caused by the shimming correction of b_5.

These effects are best described by taking the harmonic change vector as the independent variable. The changes in harmonics for multipole orders displaced by 4I from the original, where I is an integer, are then given by

$$\begin{pmatrix}\Delta b_{3+4I}\\ \Delta b_{5+4I}\\ \Delta b_{2+4I}\\ \Delta b_{4+4I}\end{pmatrix} = \begin{pmatrix}A_I & 0 & 0 & 0\\ 0 & B_I & 0 & 0\\ 0 & 0 & C_I & D_I\\ 0 & 0 & E_I & F_I\end{pmatrix}\begin{pmatrix}\Delta b_3\\ \Delta b_5\\ \Delta b_2\\ \Delta b_4\end{pmatrix} \qquad (4)$$

and

$$\begin{pmatrix}\Delta a_{3+4I}\\ \Delta a_{5+4I}\\ \Delta a_{2+4I}\\ \Delta a_{4+4I}\end{pmatrix} = \begin{pmatrix}G_I & 0 & 0 & 0\\ 0 & H_I & 0 & 0\\ 0 & 0 & J_I & K_I\\ 0 & 0 & L_I & M_I\end{pmatrix}\begin{pmatrix}\Delta a_3\\ \Delta a_5\\ \Delta a_2\\ \Delta a_4\end{pmatrix} \qquad (5)$$

Normal and skew harmonic changes are completely independent, as are even and odd multipole order changes, because the shim locations have quadrupole symmetry. The ratios between the odd harmonics generated at orders 1, 5, 9, et cetera, are fixed and constant, as are the ratios between those generated at orders 3, 7, 11, et cetera. By contrast, the change in an even order harmonic depends on the changes in both harmonic 2 and harmonic 4.

An analytical calculation based on first order perturbation theory is used to dead reckon the local corrector excitations in a single triplet, based on measurements of its three constituent quadrupoles [6]. Local correction is necessary even after adjusting the integrated goal harmonics to zero according to equation (3), because the beta functions vary rapidly in the triplet, and multipole errors in the ends of the quadrupoles can not be completely compensated by those from the body.

IV CONCLUSION

Figures 2a and 2b shows the tune footprint for on-momentum particles before and after triplet correction. The only magnetic errors present in the perturbation theory model used to get these results are the systematic errors listed in Table 2. All random harmonics are dropped, a simplifying approximation that makes little quantitative difference. In more realistic simulations it is assumed that there is a 10% error in the accuracy of measurement of individual quadrupole harmonics. Here, however, perfect knowledge of the quadrupoles is assumed. Each mesh of points represents a spectrum of particles launched with initial amplitudes between 0σ and 5σ in each plane individually, or along several contours of constant total action, $J_h + J_v$, where the ratio of horizontal and vertical actions, J_h/J_v, is smoothly varied. Chromatic tune spread (not shown) is dominated by the net positive linear and nonlinear chromaticities from the bare lattice, and not by the triplet quadrupoles, because the dispersion function is so small in the triplets.

Before correction, the tune footprint is unacceptably broad. Tuning and shimming are predicted to be very effective in reducing the spread of the footprint to a level that is negligible compared to the chromatic spread that is inevitably present. The results of the perturbation theory model shown here are consistent with more complex models that are numerically simulated, using tracking programs.

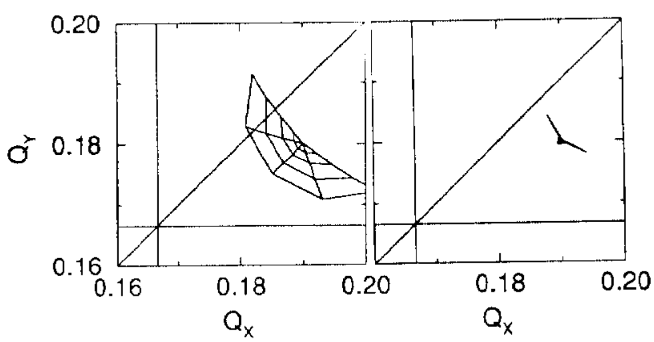

Figure 2 The tune footprint before and after correction, by shimming and excitation of the local correctors. The tune spread after correction is negligible compared to the tune spread due to linear chromaticity.

V ACKNOWLEDGEMENTS

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VI REFERENCES

[1] RHIC Design Manual, RHIC, BNL, Upton NY 11973
[2] R. Gupta et al, IEEE PAC, San Francisco (1991), p. 2239
[3] R. Gupta et al, these proceedings
[4] A. Jain and P. Wanderer, RHIC-MD-187, BNL, (1993)
[5] R. Gupta, code SHIMCAL, RHIC-MD-185 , BNL, (1992)
[6] J. Wei and M. Harrison, Int. Conf. on High Energy Accelerators, Hamburg, (1992)