# The Effect and Correction of Coupling generated by the RHIC Triplet Quadrupoles

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## I. INTRODUCTION

This study explores the possibility of operating the nominal RHIC coupling correction system in local decoupling mode, where a subset of skew quadrupoles are independently set by minimizing the coupling as locally measured by beam position monitors. The goal is to establish a correction procedure for the skew quadrupole errors in the interaction region triplets that does not rely on a priori knowledge of the individual errors.

After a description of the present coupling correction scheme envisioned for RHIC, the basics of the local decoupling method will be briefly recalled in the context of its implementation in the TEAPOT simulation code as well as operationally.

The method is then applied to the RHIC lattice: a series of simple tests establish that single triplet skew quadrupole errors can be corrected by local decoupling. More realistic correction schemes are then studied in order to correct distributed sources of skew quadrupole errors: the machine can be decoupled either by pure local decoupling or by a combination of global (minimum tune separation) and local decoupling. The different correction schemes are successively validated and evaluated by standard RHIC simulation runs with the complete set of errors and corrections. The different solutions and results are finally discussed together with their implications for the hardware.

## II. THE ORIGINAL RHIC COUPLING CORRECTION SYSTEM

The main sources of coupling in RHIC are systematic and random $a_1$ (skew quadrupole) multipoles in the dipoles and roll alignment errors in the quadrupoles. In particular, the triplet quadrupoles, strong and at a lattice position where the beta functions can be as large as 1300m, are a major source of coupling.

The coupling correction system for RHIC consists of 6 skew quadrupole families (8 quadrupoles in each family) located near the Interaction Regions (IRs) and 12 triplet correctors (1 skew quadrupole per triplet). It is worth noticing that the 6 families have in reality 12 independent power supply circuits, as described in [1].

The correction scheme presently envisioned for RHIC relies on 4 families of skew quadrupoles set up to minimize the tune separation at the nominal operating tunes of 28.19 and 29.18. A detailed description of this method can be found in [2]. The coupling effect of the triplets is corrected locally by the triplet skew quadrupole correctors by “dead reckoning” assuming that the error is known. The triplet coupling correction is part of the general triplet correction scheme, which locally compensates for triplet multipole errors. Further details about the nonlinear triplet correction system can be found in [3] and [4].

The “dead reckoning” method works well, provided we know the errors. This may not always be the case: even if the triplet quadrupoles are carefully measured and aligned at the beginning, conditions may drift and cause uncorrected residual coupling errors. An operational way of removing the coupling caused by the triplets is desirable and will be discussed below.

## III. LOCAL DECOUPLING TECHNIQUE

The local decoupling technique is part of a general method for operational corrections of errors in accelerators. The general underlying concept is to determine the settings of correctors by minimization of a *badness function* that quantifies the effect to be corrected and that is built up by *measurable quantities*. The specific badness function will vary for the different correction operations that can be performed, like closed orbit correction, decoupling, correction of beta functions and vertical dispersion. A complete discussion of this general correction approach can be found in [5]. All the correction techniques are implemented in the TEAPOT simulation code [6] in an operational way that can be easily translated into application software procedures.

A coupling badness function, that measures coupling and goes to zero in absence of coupling, is defined as:

$$B^C = \sum_{d=1}^{N^d} e_A^2 \frac{\beta_x(d)}{\beta_y(d)}$$

The summation is taken over the number of detectors (BPMs) $N^d$. The measurable quantity $e_A$ is a function of the off diagonal matrix elements $R_{A11}$ and $R_{A12}$, which can be expressed in terms of the $N_a$ skew quadrupole corrector strengths $q_a^{skew}$. When $N^d > N^a$ one can determine the skew quadrupole corrector strengths by a fitting procedure so that the following conditions are met:

$$\frac{\partial}{\partial q_a^{skew}} B^C\left(q_1^{skew} \ldots\ldots q_{N_a}^{skew}\right) = 0 \qquad a = 1, \ldots N_a$$

The local coupling algorithm has been successfully applied to correct coupling in various lattices, the SSC Boosters and Collider, and LEP. Experimental work towards the application of the method in existing machines has been carried out at HERA and LEP [7][8]. A typical criterion for coupling correction is to obtain eigenangles less than 10 degrees everywhere in the machine.

## IV. APPLICATION TO RHIC

### *A. Tests*

The decoupling algorithm has been tested in one simple case when a *single roll error* is applied to one triplet quadrupole. If we roll one of the triplet quadrupoles Q by an angle θ, the integrated skew multipole strength in the nearby corrector needed to compensate the error, can be calculated by:

$$kL = a_1(corr) = \frac{-2\theta b_1(Q)\sqrt{\beta_x(Q)\beta_y(Q)}}{\sqrt{\beta_x(corr)\beta_y(corr)}}$$

The test consists of applying a 1 mrad roll to the Q3 triplet quadrupole (and similarly to Q1 and Q2) in an otherwise ideal RHIC lattice, and checking the local coupling result versus the analytical one. The results for the Q3 quadrupole in IR6 are summarized in Table 1 below.

**Table 1: Q3 triplet quadrupole rolled by 1 mrad in the 6 o'clock (1 m β*) interaction region.**

| configuration | eigenangle max [degrees] | max vertical dispersion [m] | skew quad strength [$m^{-1}$] |
|---|---|---|---|
| no correction | 45.0 | ~0.1 | 0 |
| calculated setting | 4.6 | ~0 | -0.2119 $10^{-3}$ |
| local decoupling (1 skew) | 0.11 | ~0 | -0.2232 $10^{-3}$ |
| local decoupling (24 skews) | 0.03 | ~0 | -0.2205 $10^{-3}$ |

The first entry describes the uncorrected effect of 1 mrad roll error in the Q3 triplet quadrupole when the optics is tuned to β*=1m (in the 6 o'clock and 8 o'clock IRs). The *minimum tune separation* in this case is 0.034. The second row shows the effect of dead reckoning the correction, assuming the error known. As seen in the third row, the local decoupling algorithm can pinpoint the right correction setting when we use only the adjacent corrector strengths as a variable (1 skew case). If we activate other skew correctors distributed in the lattice (24 skew case), their strengths can be optimized to suppress virtually all coupling in the machine. The same analysis has been repeated for the Q2 and Q1 triplet quadrupoles giving similar results: it demonstrates that the local decoupling algorithm can reproduce and improve the "dead-reckoning" triplet correction without relying on a priori knowledge of the individual error.

### *B. Local decoupling schemes*

In order to study possible decoupling schemes, a random generation of skew quadrupole errors has been used in the lattice quadrupoles (triplet, IRs, arc) for the otherwise ideal RHIC lattice, in the storage configuration where 2 IRs (6 and 8 o'clock) are tuned to β*=1m and the remaining 4 IRs to β*=10m. At injection all the IRs are tuned to the higher β* and hence the coupling caused by the triplets is lower. For this study the assumptions are that we can measure coupling at every RHIC beam position monitor and that we have 12 independently powered skew quadrupole correctors located in the 12 triplets in the 6 RHIC IRs. Several solutions of the following types have been investigated:

**"pure" local solutions**: *all skew errors* are corrected by local decoupling, with the 12 skew triplet correctors (local_12) or with 24 skew correctors (local_24: 12 triplet correctors and 12 correctors from the families circuits).

**"hybrid" solutions***: arc-like errors* are corrected with 2 families set up to minimize the tune separation (global_2) and *triplet errors* are corrected with local decoupling (local_12 or local_4, where only the correctors in IR6 and IR8 are used).

When all errors, triplet included, are corrected by global decoupling, the typical residual eigenangles and minimum tune separation are 34 degrees and $10^{-2}$, confirming that the triplet correction is necessary.

Tables 2 and 3 summarize results for different seeds for the *pure local decoupling* correction and the *'hybrid'* correction scheme.

**Table 2: Correction of arc-like and triplet skew errors with 12 triplet skew correctors (local_12)**

| SEED | max eigenangle [degrees] | max vertical dispersion [m] | max skew quad kL [$m^{-1}$] |
|---|---|---|---|
| 0 | 1.7 | 0.70 | 0.813 $10^{-3}$ |
| 1 | 1.1 | 0.36 | 0.829 $10^{-3}$ |
| 2 | 2.3 | 0.12 | 0.217 $10^{-2}$ |
| 3 | 1.0 | 0.40 | 0.993 $10^{-3}$ |
| 4 | 3.4 | 0.31 | 0.483 $10^{-3}$ |
| 5 | 1.7 | 0.37 | 0.834 $10^{-3}$ |

**Table 3: "Hybrid" solution: correction of arc-like skew errors with 2 families (global_2) and triplet skew errors with local decoupling (local_12 or local_4)**

| SEED | max eigenangle [degrees] | max vertical dispersion [m] | max skew quad kL [$m^{-1}$] |
|---|---|---|---|
| 0 | 0.9 | 1.01 | 0.948 $10^{-3}$ |
| 1 | 1.1 | 0.25 | 0.610 $10^{-3}$ |
| 2 | 3.4 | 0.34 | 0.188 $10^{-2}$ |
| 3 | 1.0 | 0.52 | 0.974 $10^{-3}$ |
| 4 | 1.7 | 0.40 | 0.817 $10^{-3}$ |
| 5 | 1.1 | 0.24 | 0.873 $10^{-3}$ |

A pure local decoupling solution or a hybrid solution with 12 triplet skew quadrupole correctors are feasible on the basis of these results.

The maximum excitation allowed in the triplet C2 skew quadrupole correctors, 50 Amps, corresponds to a maximum integrated strength of 1.46 $10^{-3}$ $m^{-1}$. For the hybrid solution with 12 triplet skew quadrupoles operated in local decoupling mode, the quadrupole setting statistics over 6 seeds are:

*mean:* $< |kL| > = 0.420 * 10^{-3}\ m^{-1}$ or $< |I| > = 14.38$ A

*sigma*: $\sigma_{kL} = 0.295 * 10^{-3}\ m^{-1}$ or $\sigma_I = 10.10$ A

All the correctors are well within the system capability.

## V. SIMULATION WITH ALL ERRORS

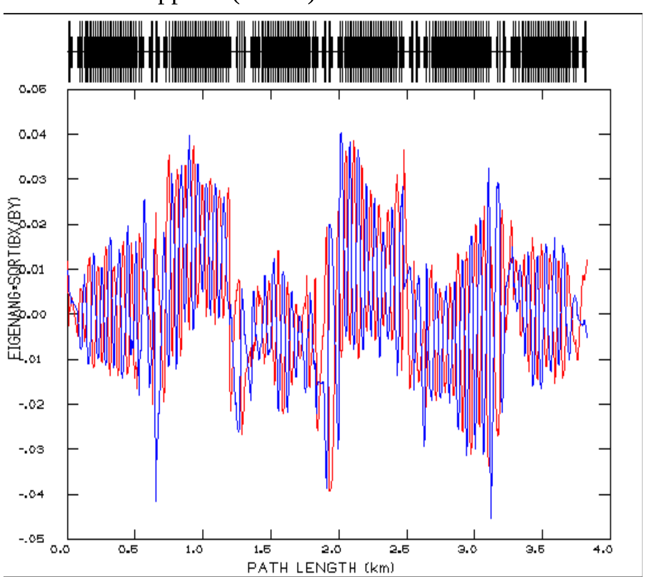
The local coupling correction of the triplet errors has been tested in the context of the full RHIC simulation, when all other errors and correction are also modelled.

The baseline 'MAC94.2' set of alignment and multipole errors, as well as the RHIC standard set of corrections (tuning, chromaticity, triplet corrections) has been used, with the "dead reckoning" compensation of triplet skew quadrupole errors substituted by local decoupling. The results for 4 error distributions are summarized in Table 4. Both the residual coupling and vertical dispersion are acceptable for RHIC, and the skew quadrupole strengths required are within the present system specifications. The resulting eigenangles are shown in Figure 1.

**Table 4: Simulation with the full set if errors and corrections**

| SEED | max eigenangle [degrees] | max vertical dispersion [m] | max skew quad $|kL|$ $[m^{-1}]$ |
|---|---|---|---|
| 0 | 3.1 | 0.34 | 0.771 $10^{-3}$ |
| 1 | 2.6 | 0.51 | 0.782 $10^{-3}$ |
| 2 | 3.7 | 0.62 | 0.778 $10^{-3}$ |
| 3 | 4.7 | 0.82 | 0.144 $10^{-3}$ |

Figure 1. The final result for the eigenangles after all error and corrections are applied (seed 1).




## VI. CONCLUSIONS

The local decoupling technique proved effective in correcting triplet skew quadrupole errors by relying only on measurable quantities. The simulation results also showed that all coupling sources in the machine could be corrected by local decoupling, should that be desirable. RHIC is adopting the solution to correct the skew quadrupole errors caused by the triplet with the 12 skew quadrupole correctors that are part of the C2 triplet corrector packages, and to rely on the minimum tune separation correction (2+2 skew quadrupole families) for correction of other coupling sources in the machine.

The old baseline corrector configuration for RHIC included power supplies only for the C2 correctors in the 6 and 8 o'clock interaction regions (low β* triplets). The 12 skew scheme presented here would require 8 more power supplies for the high β* C2 triplet correctors, a modest investment that will greatly improve the correction quality and flexibility.

For the systematic study conducted here, the assumption was made that we can measure coupling at every beam position monitor (BPM) in the machine. Only a subset of RHIC BPMs are double view, the ones located in the interaction region areas, while the BPMs in the arcs are single plane. However, it was verified that the existing 2 plane BPMs provide enough coupling information for the preferred scheme (12 skew triplet correctors) to work. In order to correct all coupling locally, coupling information from the arc is required: the local coupling algorithm implementation in TEAPOT is being extended so that the coupling at 1 arc horizontal (vertical) BPM can be inferred by measurements at the 2 adjacent vertical (horizontal) BPMs.

## VII. REFERENCES


[1] RHIC Design Manual

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