Decoupling Correction System in RHIC*

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Abstract: A global linear decoupling in the Relativistic Heavy Ion Collider (RHIC) is going to be performed with the three families of skew quadrupoles. The operating horizontal and vertical betatron tunes in the RHIC will be separated by one unit $\nu_x=28.19$ and $\nu_y=29.18$. The linear coupling is corrected by minimizing the tune splitting $\Delta\nu$ the off diagonal matrix m (defined by Edwards and Teng¹). The skew quadrupole correction system is located close to the each of the six interaction regions. A detail study of the system is presented by the use of the TEAPOT² accelerator physics code.

1. Introduction

The horizontal and vertical motion of the particles in the storage ring is always coupled as a consequence of unavoidable imperfections in construction and alignment of the magnets. In the RHIC at injection a dominant source of the linear coupling are the superconducting dipoles. The skew quadrupole a_1 is present in magnetic multipoles due to the construction error from the coil tolerances. At the same time there are always errors in the quadrupole rolls which is a combination of the uncertainty in the orientation of the magnetic field planes and the installation errors in the tunnel. At the RHIC top energy the dominant source of the linear coupling are the errors and misalignment of the insertion triplet quadrupoles. The two detectors STAR and PHENICS will have solenoidal magnetic field within which was an additional source of coupling taken into account. The horizontal and vertical betatron functions at the high energy (when at the center of the two insertions the beam is squeezed to a minimum with $\beta_x = \beta_y = 1$ m) have maxima value at the second quadrupole triplet of $\beta_x = 1359$ m and $\beta_y = 1340$ m, respectively. A separate skew quadrupole correctors are a part of the special corrector system placed at the quadrupole triplets to do the correction of the a_1 magnetic multipole in the triplets³.

2. Split Tunes Operation

The horizontal and vertical betatron tunes in RHIC will be separated by one unit to allow easier correction of the linear coupling-resonance $\nu = \nu_x - \nu_y$. To show the effectiveness of this tune separation an "experiment" in RHIC was performed by using the TEAPOT. For the source of coupling an error in the systematic skew quadrupole multipole of $a_1 = -2.5$ units in the RHIC dipoles was introduced (in RHIC one unit is defined as 10^{-4} part the dipole magnetic field strength at the distance of 2.5 cm of the central field axis). The fractional parts of the horizontal and betatron tunes were set to be equal. The minimum tune splitting $\Delta\nu$, when the skew quadrupoles were introduced, were measured in two cases:

- first with the integer parts of the tunes being equal, $\nu_x = \nu_y = 28.823$, with a result for the tune splitting of: $\Delta\nu = 0.20073$, and the
- second with the integer parts separated by one unit $\nu_x = 28.197$ and $\nu_y = 29.197$, with a result for the tune splitting of: $\Delta\nu = 0.01998$.

A choice of the lattice with separated tunes allows easier decoupling of the machine. Additional advantages with respect to the lattice with equal integer parts of the tunes are that the phase difference between the two low beta interaction regions ($\beta^* = 1$) is very close to the preferable value of $\Delta\nu = \pi/2$ and the second order tune shift induced by the sextupoles is smaller.

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3. Method of Correction

The linear decoupling of RHIC accelerator will be performed globally as it has been done at Fermilab Tevatron and the Main Ring as well as at HERA, accelerators. The fractional parts of the transverse tunes will be brought close together and the accelerator will be decoupled by adjustment of the skew quadrupoles and the main quadrupoles circuits. This should bring the minimum tune splitting $\Delta\nu$ close to zero. A beam transport is characterized by 6x6 transfer matrix which was written⁴ in the form of:

$$T = \begin{pmatrix} M & m & d_1 \\ n & N & d_2 \\ e_1 & e_2 & F \end{pmatrix} \quad T^{-1} = \begin{pmatrix} \bar{M} & \bar{n} & \bar{e}_1 \\ m & N & \bar{e}_2 \\ \bar{d}_1 & \bar{d}_2 & \bar{F} \end{pmatrix}$$

where the six dynamic variables are $x, x'=dx/ds, y, y', -\Delta s, \Delta p/p$, and the matrix $T = T^\dagger$ is symplectic. If the T is restricted to the 4x4 matrix then¹ it could be parameterized as:

$$T = \begin{pmatrix} M & m \\ n & N \end{pmatrix} = U \begin{pmatrix} A & O \\ O & B \end{pmatrix} U^\dagger$$

where the U matrix is defined as:

$$U = \begin{pmatrix} I \cos\phi & D \sin\phi \\ \dagger & \\ -D \sin\phi & I \cos\phi \end{pmatrix}$$

while:

$$D = (m + n^\dagger)/\Delta,$$

$$\Delta = \sqrt{[\det(m + n^\dagger)]}$$

$$\tan 2\phi = \Delta / [\text{Trace}(M - N)/2],$$

and: $A = M - D \cdot n \tan\phi$, $B = N + D^\dagger \cdot m \tan\phi$. A new matrix h is defined as: $h = m + n^\dagger$.

The normal modes eigen angles of the transverse coupled motion m_1 and m_2 are defined from the above matrix equation:

$$[1/2 \text{Trace} A - 1/2 \text{Trace} B]^2 = [1/2 \text{Trace} M - 1/2 \text{Trace} N]^2 + \Delta^2,$$

or

$$[\cos\mu_1 - \cos\mu_2]^2 = (\cos\mu_x - \cos\mu_y)^2 + \Delta^2,$$

where the μ_x and μ_y are the nominal horizontal and vertical tunes. The motion is considered uncoupled if the $\Delta=0$. This is fulfilled if $\det(h)=0$. The elements of the matrix h were obtained from the TEAPOT transfer matrix (6x6) which traces the coupled particle motion through the accelerator. The determinant of the matrix h will be zero if elements in one of the matrix lines or rows are equal to zero. Four conditions were required to be fulfilled: the tunes ν_x and ν_y should remain the same and the determinant of the matrix h should be zero (constraints: $\nu_x, \nu_y, h_{1,1}=0$, and $h_{1,2}=0$) which was accomplished by varying the horizontal and vertical focussing quadrupoles and the two families of the skew quadrupoles (variables: $q_x, q_y, q_{sk1}, q_{sk2}$).

4. Correction System

The global decoupling of the RHIC lattice, with betatron tunes separated by one unit, is achieved with three families of skew quadrupoles. The families are presented in **Table 1** and **Table 2**. **Table 1** represents the families in the case of the lattice with $\beta^*=10$ m for all the interaction regions, while **Table 2** represents the the same families for the lattice at the top RHIC energy when the two interaction regions are at the low beta $\beta^*=1$ m. Each family is defined according to the phases $\Phi=\phi_x-\phi_y$ of the skew quadrupoles. There are six interaction regions at RHIC and they are marked as clock hours.

TABLE 1

Int. Region	Family	Φ	Polarity
6H	# 1	150°	+
8H	# 2	95°	+
10H	# 3	30°	+
12H	# 1	330°	-
2H	# 2	275°	-
4H	# 3	210°	-

TABLE 2

Int. Region	Family	Φ	Polarity
6H	# 1	210°	+
8H	# 2	145°	+
10H	# 3	90°	+
12H	# 1	30°	-
2H	# 2	325°	-
4H	# 3	270°	-

5. Ability of the Correction System

There are two kinds of corrector packages in RHIC. The regular package includes on one side of the cryostat the dipole corrector, in the middle of the cryostat the main quadrupoles, and at the end the sextupole corrector (CQS). The elements of the CQS package are all at the liquid helium temperature of ~ 4.5 K. There are special four layers correctors within the first part of the CQS cryostat which represents the second kind of the corrector package. The corrector coils are concentrically inclosed around the stainless steel beam pipe. The first superconducting cable at the inner radius forms the ten decapole coils, the second layer consists of eight octupole coils, followed by the layer of four quadrupole coils with the last layer made of two dipole coils. The skew quadrupole corrector, marked in figure 1 as a_1 , is located within the second type of the CQS where the third corrector layer includes four skew quadrupole coils.

Figure 1 The skew quadrupole locations in the RHIC ring.

The correction ability of the system was measured by the value of the minimum tune split at the top energy. Again the tracking program TEAPOT was used as a tool. The unperturbed settings for the horizontal and vertical betatron tunes were $\nu_x=28.197$ and $\nu_y=29.197$, respectively. The strength of all three families of the skew quadrupoles was set to the same absolute values of $kL=0.001785$ 1/m (this is a nominal correction quad strengths at the top energy - corresponds to the current $I=50$ A). The above result of the quad strength was obtained from the reported⁵ quadrupole measurements. The amplitude of the resulting vector is four times the amplitude of each of the six vectors on the three circuits. The measured minimum tunes split, with the TEAPOT, was $\Delta\nu=0.1969$.

Table 3

Magnetic field (T)	Current (A)	@ Radius (m)	Eff. Length (m)
B=0.0675 T	I=49.8	$R_0 = 0.025$	L=0.555

Another set of "measurements", with the split tune lattice, was performed by the TEAPOT. Different sources of coupling were introduced and the minimum tune split was measured:

-The systematic skew quadrupole multipole in the dipoles which was set to be $a_1=-4.0$ units⁵ produced a tune splitting of $\Delta\nu=0.05037$.

-When the same systematic and the random error in the dipoles were put together with the quad random misalignment errors in the horizontal and vertical axes of $\sigma_x=1$ mm and $\sigma_y=1$ mm, respectively, and with an overestimated random errors of the quadrupole rolls of $\sigma_\theta=3$ mrad, the minimum tune split measured was $\Delta\nu=0.0552$.

-The minimum tune splitting measured $\Delta\nu=0.07987$ when the systematic error of the skew quadrupole a_1 in the dipoles was put in with the opposite sign as $a_1=4.0$ units, together with the other quadrupole errors mentioned above.

-The maximum value of the tune splitting $\Delta\nu=0.10231$ was obtained under specific conditions: all systematic and random multipole errors in the quadrupoles with quadrupole misalignment errors of $\Delta x=1$ mm and $\Delta y=1$ mm, and with the overestimated quad rotation error of $\sigma_\theta=3$ mrad. The skew systematic and random quadrupole multipole within the dipoles were lowered to a value of $a_1=-2.5$.

A prediction for the minimum tune splitting arising from the quadrupole roll errors ($\Delta\theta$) and vertical orbit errors (Δy) through the sextupoles for the lattice composed of the regular FODO cells is⁷: $(\Delta\nu)_{rms} = \kappa/2\pi\sqrt{N} \beta_{typ} [4\langle(\Delta\theta)^2\rangle + (\Delta y)^2/\langle\eta_{typ}\rangle^2]^{1/2}$, where κ is the quadrupole strength ($\kappa\approx 0.08$ 1/m), β_{typ} is the betatron function ($\beta_{typ} \approx R/v = 610\text{m}/29.2 \approx 21$ m), $\Delta\theta$ is the rotation error of the quads ($\sigma_\theta = 3$ mrad), N is the number of quadrupoles ($N\approx 161$), η_{typ} is the typical dispersion in the FODO lattice $\eta_{typ}\approx R/v^2\approx 0.8$ m, Δy is the vertical closed orbit error $\Delta y=1$ mm. The minimum tune splitting $\Delta\nu_{min}$ calculated to be: $\Delta\nu_{min} = 0.021$. A result from the simulation with the program TEAPOT was $\Delta\nu=0.0447$.

In recent dynamical aperture studies (end of 1993) the average values of the current through the skew quadrupoles to decouple the machine, at injection as well as at the top energies, were between 4-25 A (nominal current 50 A). In these studies all expected errors in misalignment and rolls, multipole systematic and random errors in magnets were included.

6. Additional Possibilities of the Correction System

The additional skew quadrupoles, presented in figure 1 are placed at the corrector elements locations 4 and 5 at all the interaction regions (total number of 24). These quadrupoles which are located around the *Star* and *Phenix* detectors at 6H and 8H interaction regions could be used for compensation of the solenoidal fields from the detectors. The remaining quadrupoles which are not connected to the power supply in figure 1 could be used for the compensation of the vertical dispersion which comes from the skew quadrupoles.

References:

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