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Abstract

The global betatron decoupling on the ramp is an important issue for the operation of the Relativistic Heavy Ion Collider (RHIC), especially in the RHIC polarized proton (pp) run. To avoid the major betatron and spin resonances on the ramp, the betatron tunes are constrained into a very tight space. And the rms value of the vertical closed orbit should be smaller than 0.5mm. Both require the global coupling on the ramp to be well corrected. Several ramp decoupling schemes were found and tested at RHIC, like N-turn map decoupling, three-ramp correction, coupling amplitude modulation, and coupling phase modulation. In this article, the principles of these methods are shortly reviewed and compared. Among them, coupling angle modulation is a robust and fast one. It has been applied to the global decoupling in the routine RHIC operation.

INTRODUCTION

The global betatron decoupling on the ramp is an important issue for the operation of the Relativistic Heavy Ion Collider (RHIC), especially in the RHIC polarized proton (pp) run. To avoid betatron and spin resonance line crossings and the beam polarization loss on the ramp, the betatron tunes are constrained into a very tight space. And the rms value of the vertical closed orbit should be smaller than 0.5mm. Both of them require the global coupling on the ramp to be well corrected.

The betatron coupling on the ramp can be identified with the turn-by-turn beam position monitor (BPM) data from the tune meter kicked beam. The tune meter kicker kicks one bucket bunch on the ramp per 2 second. Under the coupled situation, the transverse oscillation amplitude beating of the horizontal and vertical betatron motions are observed. And normally there are double peaks in the fast Fourier transformation (FFT) spectrum of the horizontal and vertical betatron oscillations.

The global decoupling on the ramp is more difficult than that at injection and store. Besides the non-stop energy acceleration, the beam optics evolves. The main dipole strength snapback, transition, and beta squeezing all pose challenges to the global decoupling. The movement of the closed orbit, especially the vertical closed orbit in the sextupoles, changes the coupling situation on the ramp. The RHIC energy ramp takes about 220 seconds. And the rotator ramp at the energy flattop takes about 430 seconds. Therefore, a fast and robust global decoupling scheme and reliable instrumentations are needed.

The conventional skew quadrupole strength scan is not applicable for the ramp coupling correction. As a logical extension, the skew quadrupole modulation was put forth to hopefully fulfill the global decoupling on the ramp. The skew quadrupole modulation includes the coupling amplitude modulation and the coupling angle modulation [1, 2, 3]. The coupling amplitude modulation gives the residual coupling's projections onto the skew quadrupole modulation directions. The coupling angle modulation gives the coupling correction strengths. The tune changes during the skew quadrupole modulation are tracked with the phase lock loop (PLL) system [4, 5]. Besides the skew quadrupole modulation, N-turn transfer map decoupling and three-ramp decoupling schemes were also tested at the RHIC. All the above schemes are used in the feed-forward mode. The global decoupling in the feedback mode is being investigated at RHIC based on the six global coupling observables. The phase loop and amplitude ratio loop are promising for the future decoupling feedback [6].

In the following, we first quickly review the principles for the decoupling s methods on the ramp. Then, decoupling examples with the coupling angle modulation are given.

RAMP DECOUPLING SCHEMES

N-turn transfer maps [7]

At one point in the ring, the 4×4 linear transfer matrix of the betatron motion is given by

$$\mathbf{T} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix}. \quad (1)$$

To decouple the matrix $\mathbf{M}$ is equivalent to meet $\mathbf{C}+\overline{\mathbf{B}} = \mathbf{0}$. To be able to observe the maximum effect of the transverse energy beating, Fischer calculates the N-turn transfer matrix $\mathbf{M}^N$ instead of the one-turn transfer matrix $\mathbf{M}$. N is the revolution turn number given by the half energy beating period due to the coupling,

$$N = \frac{\pi}{|Q_1 - Q_2|}. \quad (2)$$

Here $Q_{1,2}$ are the two eigen tunes. $(\mathbf{C}+\overline{\mathbf{B}})$ can be determined from the N-turn matrix $\mathbf{M}^N$,

$$\mathbf{C}+\overline{\mathbf{B}} = (\mathbf{C}_N + \overline{\mathbf{B}}_N)\frac{\cos Q_1 - \cos Q_2}{\cos(NQ_1) - \cos(NQ_2)}. \quad (3)$$

The two eigen tunes are obtained from the fast Fourier transformation of the turn-by-turn BPM data. The N-turn transfer matrix $\mathbf{M}^N$ is obtained through the fitting. Knowing $\mathbf{C}+\overline{\mathbf{B}}$, the one-turn matrix is decoupled with the skew

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quadrupole families according to the thin skew quadrupole and weak coupling approximations.

This method has been successfully applied to the RHIC injection coupling correction. The turn-by-turn BPM data are taken from the injected beam. On the RHIC ramp, the turn-by-turn BPM data are taken from the tune meter kicking. This method is still being tested for the ramp coupling correction.

3-ramp correction

From the linear difference coupling's Hamiltonian perturbation theory [8, 9, 10, 11], the eigen tune split ΔQ is

$$|\Delta Q| = \sqrt{\Delta^2 + |C^-|^2}. \tag{4}$$

Here Δ is the uncoupled tune split. C^- is the coupling coefficient,

$$C^- = |C^-|e^{i\chi} = \frac{1}{2\pi}\oint \sqrt{\beta_x\beta_y}k_s e^{i(\Phi_x - \Phi_y - \Delta\frac{2\pi s}{L})}dl. \tag{5}$$

$|C^-|$ is the coupling amplitude, χ is the angle of the coupling. C^- normally is a complex number.

The total coupling coefficient C^-_{tot} in the ring is

$$C^-_{tot} = C^-_{res} + C^-_{int}, \tag{6}$$

where C^-_{res} is the residual coupling, C^-_{int} is the introduced coupling coefficient.

In Eq. (4), there are three real unknowns, Δ, real and imaginary parts of C^-. Therefore, Trbojevic suggested using three ramps to determine the residual coupling at one specific ramp time point. For each ramp, we change the settings of the skew quadruople families, the introduced C^-_{int} can be calculated from the optics model.

The shortcoming of this method is apparent. It requires three ramps, which is very expensive. And this method has tight connections to the optics since C^-_{int} is calculated from the optics model. This method is the last choice for the ramp coupling correction.

Coupling amplitude modulation [2]

As a logical extension, skew quadrupole modulation was put forth to hopefully fulfill the ramp coupling correction. The skew quadrupole modulation includes coupling amplitude modulation and coupling angle modulation. Coupling angle modulation will be discussed in next section in detailed.

The introduced coupling by the coupling amplitude modulation is

$$C^-_{mod} = C^-_{mod,amp}\sin(2\pi f t). \tag{7}$$

f is the modulation frequency. $C^-_{mod,amp}$ is the modulation amplitude.

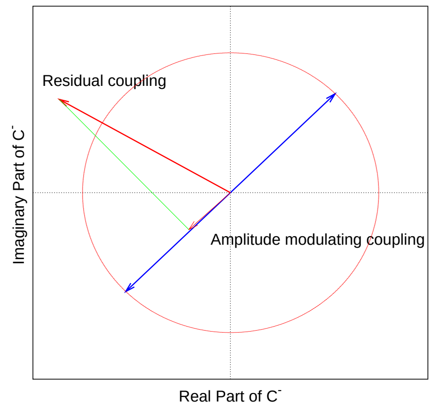

Figure 1: Schematic plot of coupling amplitude modulation.

Then, according to Eq. (4), the eigen tune split during the modulation is

$$\begin{aligned}(Q_1 - Q_2)^2 \quad &= \quad \Delta^2 + |C^-_{res}|^2 + \frac{1}{2}|C^-_{mod,amp}|^2 \\ &+2|C^-_{res}||C^-_{mod,amp}|\cos(\varphi)\sin(2\pi f t) \\ &-\frac{1}{2}|C^-_{mod,amp}|^2\cos(4\pi f t),\end{aligned} \tag{8}$$

where φ is the angle difference between C^-_{res} and $C^-_{mod,amp}$. $|C^-_{res}|\cos(\varphi)$ is the projection of the residual coupling onto the modulation coupling direction.

We define the projection ratio k as

$$\kappa = \frac{|C^-_{res}|\cos(\varphi)}{|C^-_{mod,amp}|}. \tag{9}$$

According to Eq. (8), it can be determined from the FFT of $(Q_1 - Q_2)^2$. If the $1f$ and $2f$ peaks' amplitudes are A_{1f} and A_{2f}, respectively,

$$|\kappa| = (\frac{A_{1f}}{A_{2f}})/4. \tag{10}$$

Knowing the projections of the residual coupling onto at least two skew quadrupole modulation direction, the residual coupling coefficient can be determined and eventually compensated. The schematic plot of coupling amplitude modulation is shown in Figure. 1.

This method was tested in RHIC'04. The skew quadrupole modulation frequency was chosen 0.2 Hz on the ramp. Linear regression fitting was used to greatly reduce the modulation time to below 10 seconds. However, it is still not fast and robust enough to fulfill the ramp coupling correction.

COUPLING ANGLE MODULATION

Coupling angle modulation was proved to be a fast and robust global decoupling method. It was quickly experimentally verified at RHIC injection and store. Now it has been applied to the RHIC ramp coupling corrections.

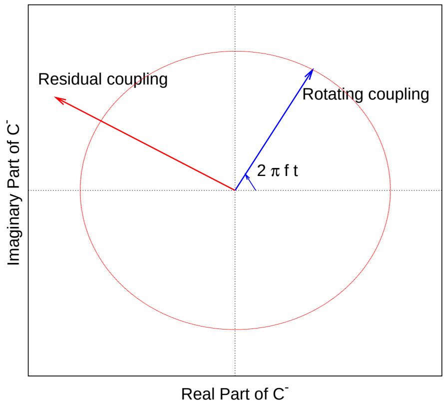

Figure 2: Schematic plot of the coupling angle modulation.

Principle [1]

This method modulates two orthogonal skew quadrupole families. The coupling coefficients contributed by the orthogonal families differ by $90°$. If their coupling coefficient modulation amplitudes and modulation frequencies are same, and there is a $90°$ difference in their initial modulation phases, the total introduced coupling coefficient is

$$C^-_{mod} = |C^-_{mod,amp}| \cdot e^{i2\pi ft}, \tag{11}$$

where f is the modulation frequency, and $|C^-_{mod,amp}|$ is the coupling modulation amplitude. Figure. 2 shows the schematic plot of the coupling angle modulation.

According to Eq. (4), the tune split's square during the modulation is

$$\begin{aligned}|\Delta Q|^2 \;=\;& \Delta^2 + |C^-_{res}|^2 + |C^-_{mod,amp}|^2 \\ & +2|C^-_{res}||C^-_{mod,amp}| \cos(2\pi ft - \phi_{res}).\end{aligned} \tag{12}$$

Assuming the rotating coupling's amplitude $|C^-_{mod,amp}|$ is constant during the coupling angle modulation, we define

$$|C^-_{res,amp}| = k\, |C^-_{mod,amp}|. \tag{13}$$

k is a non-negative number. Then, the maximum and minimum tune split's squares are

$$\Delta Q^2_{min} = \Delta^2 + (k-1)^2 \cdot |C^-_{mod,amp}|^2, \tag{14}$$

$$\Delta Q^2_{max} = \Delta^2 + (k+1)^2 \cdot |C^-_{mod,amp}|^2. \tag{15}$$

Together with the tune split square ΔQ^2_0 without modulation,

$$\Delta Q^2_0 = \Delta^2 + k^2 \cdot |C^-_{mod,amp}|^2, \tag{16}$$

the factor k is determined,

$$k = [4(\frac{\Delta Q^2_{max} - \Delta Q^2_0}{\Delta Q^2_{max} - \Delta Q^2_{min}} - \frac{1}{2})]^{-1}. \tag{17}$$

The factor k has a significant role in determining of the correction strengths of the global coupling. The minimum tune split is obtained when the rotating coupling takes the opposite direction to the residual coupling. Therefore, the right decoupling skew quadrupole strengths' combination is given at the minimum tune split time stamp. Since the skew quadrupole modulation currents are known at that time point, according to Eq. (13) and Eq. (17) , the global decoupling strengths are determined. That is, The correction strengths are the the modulating skew quadrupole strengths at the minimum tune split multiplied by the factor k.

This method cleverly links the global coupling correction strengths with the modulating skew quadruple family strengths through the rotating coupling. The ratios of the modulating skew quadrupole families give the right decoupling direction. This method just needs the minimum and maximum tune split during the modulation, so it is insensitive to the detailed PLL tunes. And the exact modulation amplitude combination of the skew quadrupole families is proved to be not strictly required. This scheme is less connected to the optics model. Therefore, this method is robust. Since the the minimum and maximum tune splits can be obtained in one modulation period, this method is fast, too. The data processing is also simple.

Verifying at injection and store

Coupling angle modulation correction was first tested at RHIC injection and store. Here we gave an example of decoupling at the RHIC Blue ring at store. Fig. 3 shows the PLL tune during one complete coupling angle modulation coupling correction. After putting the correction strength into, the two eigen tune split was greatly reduced. FIG. 4 shows the modulating skew quadrupole power supply currents and the tune split square $|\Delta Q|^2$. Before the coupling correction, $\Delta Q_{min} = 0.0078$. After coupling correction, $\Delta Q_{min} = 0.0006$. The residual coupling was considerably corrected.

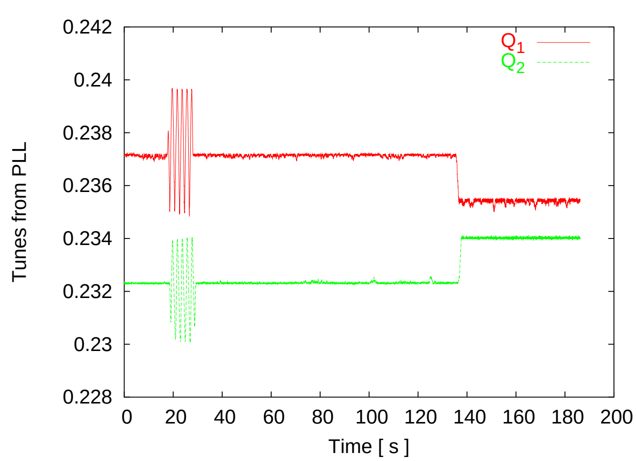

Figure 3: The tunes during the coupling angle modulation at Blue store.

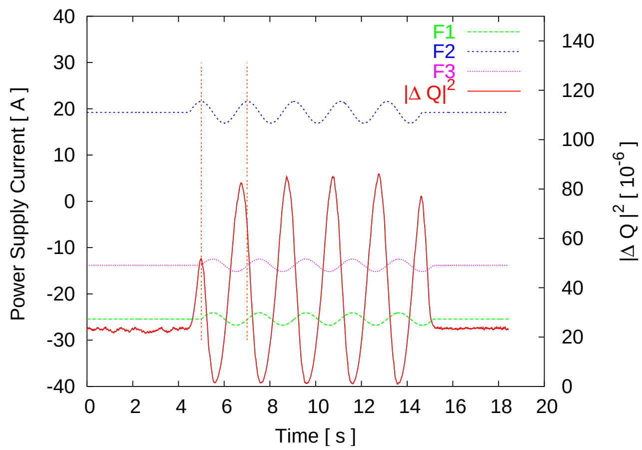

Figure 4: The coupling correction strength searching.

Applying to ramp

The whole RHIC 2005 pp energy ramp takes about 220 seconds. The rotator ramp takes about 430 seconds at energy flattop. Fig. 5 shows the yellow PLL tunes from the coupling angle modulation in the first ramp fill 6817. The PLL system gives 177 tune points every one second. In Fig. 5, only the PLL tunes in the first 140 seconds of the energy ramp are shown. After 140 seconds from the ramp starting point, there is a tune swing for both tunes.

Fig. 6 shows the second ramp PLL tune data. The correction strengths from the first ramp were put into this ramp fill 6818. Comparing the tune splits before and after coupling correction, the coupling are greatly reduced. After the global decoupling, the tunes were easy to move in the ramp development.

During the application of the coupling angle modulation correction to the ramp, we found sometime it is hard to get the exact k factor for the full coupling correction like at injection and store. This is due to the tune evolves even in less than ten seconds. According to the experiences at the RHIC, the most important issue for the coupling angle modulation correction on the ramp is to obtain the valid PLL tune data. PLL tune losing lock was seen under some coupling situation.

CONCLUSION

The global betatron decoupling on the ramp is an important issue for the operation of the Relativistic Heavy Ion Collider (RHIC), especially in the RHIC polarized proton run. Several decoupling schemes were found and tested at RHIC, like N-turn map decoupling, three-ramp correction, coupling amplitude modulation, and coupling phase modulation. Among them, coupling angle modulation is a robust and fast one. It has been applied to the RHIC'05 pp run. The possible global decoupling in the feedback mode with eigen mode amplitude ratios and phase differences are being tested at the RHIC.

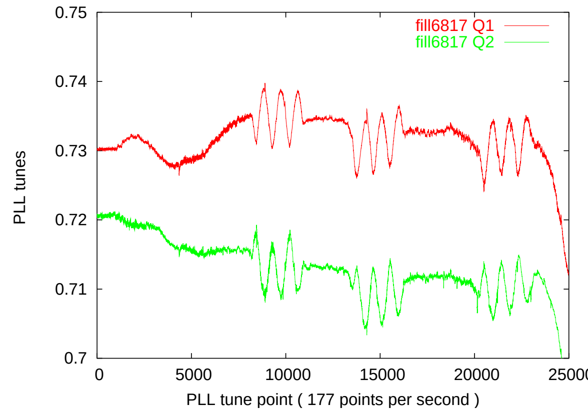

Figure 5: The PLL tunes from the coupling angle modulation.

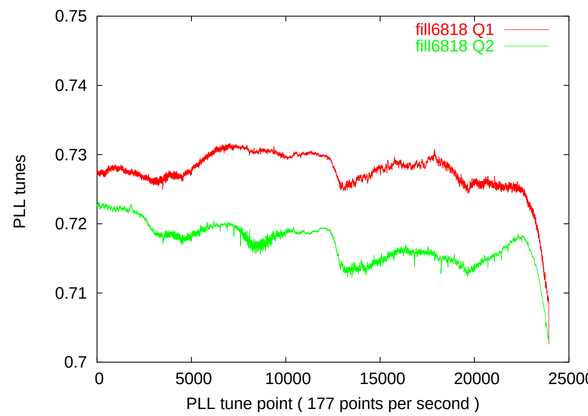

Figure 6: The PLL tunes after the coupling corrections.

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