GLOBAL DECOUPLING ON THE RHIC RAMP*

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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. 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 decoupling on the ramp is more difficult than that at injection and store. Besides the non-stop energy acceleration, the beam optics evolves. The 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 on the ramp. The RHIC pp run's main 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 fulfill the global decoupling on the ramp. Either the coupling amplitude or coupling angle can be modulated [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) tune measurement 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 [6].

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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

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix}. \tag{1}$$

To decouple globally is equivalent to meet $\mathbf{C} + \overline{\mathbf{B}} = \mathbf{0}$. To be able to observe the maximum effect of the transverse 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 transverse beating period due to the coupling,

$$N \sim \frac{\pi}{|Q_1 - Q_2|}. \tag{2}$$

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

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

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

This method has been successfully applied at injection, where it can decouple within seconds after a bunch was taken. However, so far it failed to work on ramps. In previous years the quality of the turn-by-turn orbit data did not allow a reliable fit of the N-turn map. These difficulties were resolved, and the same N-turn map is now calculated for consecutive ramps. The method calculates the effect of the skew correctors from an online model. At higher energies (and lower β^*), the model is not accurate enough any more, and the wrong corrector strenght are calculated. To overcome this problem, the phases of the skew correctors may need to be fitted from experimental data.

3-ramp correction

From the linear difference coupling's Hamiltonian perturbation theory [8, 9, 10, 11], the eigentune 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. 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]

Skew quadrupole modulation was proposed for the ramp coupling correction. The skew quadrupole modulation can be either coupling amplitude modulation or 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.

Then, according to Eq. (4), the eigentune 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 $\kappa = |C^-_{res}|\cos(\varphi)/|C^-_{mod,amp}|$. 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, $|\kappa| = A_{1f}/(4A_{2f})$. 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.

This method was tested in RHIC in 2004. The skew quadrupole modulation frequency for the ramp was chosen as 0.2 Hz. Linear regression fitting was used to greatly reduce the modulation time to below 10 seconds. However, it is still not fast and robust enough for the ramp coupling correction.

COUPLING ANGLE MODULATION

Coupling angle modulation was proved to be a fast and robust global decoupling method. It was experimentally verified at RHIC injection and store, and has also been applied to the RHIC ramp.

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

$$C^-_{mod} = |C^-_{mod,amp}| \cdot e^{i2\pi f t}, \tag{9}$$

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

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

$$\begin{aligned}|\Delta Q|^2 \quad = \quad & \Delta^2 + |C^-_{res}|^2 + |C^-_{mod,amp}|^2 \\ & +2|C^-_{res}||C^-_{mod,amp}|\cos(2\pi f t - \phi_{res}). \end{aligned} \tag{10}$$

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

$$|C^-_{res,amp}| = k\,|C^-_{mod,amp}|. \tag{11}$$

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

$$\Delta Q^2_{min} = \Delta^2 + (k-1)^2 \cdot |C^-_{mod,amp}|^2, \tag{12}$$

$$\Delta Q^2_{max} = \Delta^2 + (k+1)^2 \cdot |C^-_{mod,amp}|^2. \tag{13}$$

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

$$\Delta Q^2_0 = \Delta^2 + k^2 \cdot |C^-_{mod,amp}|^2, \tag{14}$$

the factor k is determined,

$$k = \left[4\left(\frac{\Delta Q^2_{max} - \Delta Q^2_0}{\Delta Q^2_{max} - \Delta Q^2_{min}} - \frac{1}{2}\right)\right]^{-1}. \tag{15}$$

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. (11) and Eq. (15) , the global decoupling strengths are determined. That is, The correction strengths are the modulating skew quadrupole strengths at the minimum tune split multiplied by the factor k.

RHIC Modulation Setup

Each RHIC ring has three correction skew quadrupole families, F1, F2 and F3, each having 12 skew quadrupole magnets, with four activating power supplies. To produce the rotating coupling coefficient, we use skew quadrupole families F1 and F3 to generate a new skew quadrupole family (F1F3) that is orthogonal to the coupling contribution only from family F2. To equalize families (F1F3) and F2's coupling modulation amplitudes, the amplitudes of modulation strengths for families F1 and F3 are set to $\frac{1}{\sqrt{3}}$ of that of family F2. To get a 90° difference in the initial modulation phases, family F2 modulation starts a quarter period earlier than families F1 and F3.

Applying to ramp

The whole RHIC 2005 pp run's main ramp takes about 220 seconds. The rotator ramp takes about 430 seconds at energy flattop. Fig. 1 shows the yellow tunes from the coupling angle modulation in the first ramp fill 6817. In Fig. 1, only the 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. The skew quadrupole modulation frequency is 0.2 Hz. In Fig. 1, each modulation took 15 seconds, or three modulation periods.

Fig. 2 shows the second ramp tune data with coupling corrections. 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 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 because of the tune changes. According to the experiences at RHIC, the most important issue for the coupling angle modulation correction on the ramp is to obtain valid PLL tune data. PLL tune losing lock was seen under some coupling situation.

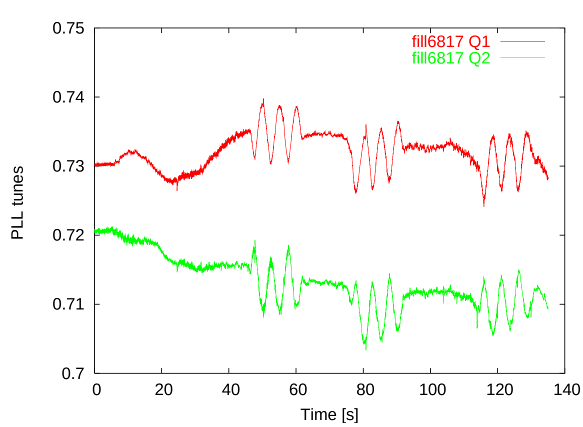

Figure 1: The tunes from the coupling angle modulation.

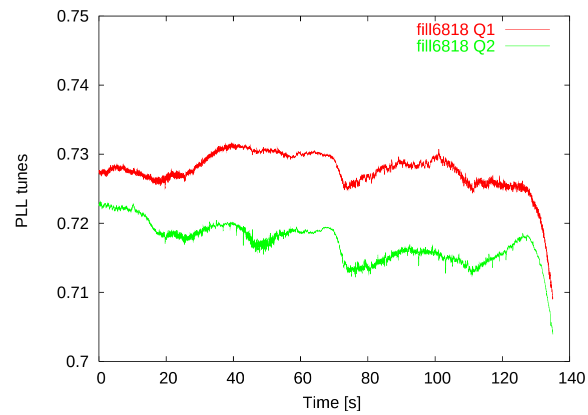

Figure 2: The tunes after the coupling corrections.

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, and the most promising of the tried methods. 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.

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