OPTIMIZE THE ALGORITHM FOR THE GLOBAL ORBIT FEEDBACK AT FIXED ENERGIES AND DURING ACCELERATION IN RHIC*

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Abstract

To combat triplets vibration, the global orbit feedback system with frequency about 10 Hz was developed and engaged in operation at injection and top energy in 2010, during beam acceleration in 2012 at RHIC. The system has performed well with keeping 6 out of 12 eigenvalues for the orbit response matrix. However, we observed corrector current transients with the lattice for polarized proton program in 2015 which resulted in corrector power supply trips. In this report, we will present the observation, analyze the cause and also optimize the feedback algorithm to overcome the newly emerged problem with the feedback system.

INTRODUCTION

RHIC comprises two circular counter-rotating accelerators in a common horizontal plane, which are oriented to intersect one another at six interaction points (IPs) with two colliding beam experiments (STAR and PHENIX) [1]. Each ring consists of three inner arcs and three outer arcs with six insertions joining them. The DX dipole magnets bring the beams together for head-on collisions at IPs for experiments. They are the only common bending magnets for both rings. The triplets (Q1, Q2 and Q3 quadrupole magnets) focus the beam for small beam sizes at IPs. The triplets and D0 magnets on the same side of IP for the two rings were installed in the same cryostat.

Horizontal orbit jitter around 10 Hz was observed in both rings in the early days by measuring the beam positions [2]. Triplets vibration was suspected since its strong focusing and the sharing of cryostat of triplets from both rings. This hypothesis was later confirmed by offline modeling and measurement by accelerometer of the triplet vibrations with frequency around 10 Hz. Later on, oscillation of Helium flow pressure around 10 Hz was measured as well [3, 4].

The orbit jitter will affect the beam parameters and machine performance in many ways [5]. The orbit jitter caused by Helium-induced triplet vibration would introduce orbital and angular jitter at the IPs, which will diminish the luminosity. The orbit jitter in sextupoles will introduce tune modulations, which would affect dynamic aperture and therefore beam lifetime. The orbit jitter at collimators and experimental area would result in oscillating background. The precision of beam measurements were dominated by the presence of 10 Hz orbit oscillation.

Several solutions were proposed to combat the orbit jitter problem over the years [6, 7]. Stiffening of the mechanical supports of the magnet was suggested to increase the resonant frequencies of the triplet. A linear shock absorber attached to outside support can damp the triplet vibration passively. Two linear actuators connected to each end of the cold mass provide forces proportional and opposite to the velocities of both ends of the cold mass would damp the vibration actively. A local orbit feedback system with small corrector dipoles at the two ends of the cryostat to compensate both position and angle was designed and tested. The 10 Hz global orbit feedback system with correctors located close to triplets, which correct the orbit oscillation reported by fast BPMs globally was designed and implemented for operation successfully.

ORBIT FEEDBACK SYSTEM OVERVIEW

The 10 Hz global orbit feedback system [8] was designed to correct the 10 Hz horizontal beam perturbations in both rings that are caused by Helium induced triplet vibration. The full system in each ring consists of 36 BPMs, corresponding to 2 per triplet in each of the 12 triplet locations and two in each of the 6 arcs, and 1 dipole corrector at each triplet location for a total of 12 correctors. The standard RHIC BPM Integrated Front End (IFE) electronic modules were equipped with new daughter card for 10 kHz position data distribution [9]. The correctors are compact "window-frame" horizontal laminated yoke magnets due to space limitations. A small fringe field from each magnet, overlapping the opposite RHIC ring, is compensated by a correction winding placed on the opposite ring's magnet and connected in series with the main winding of the first one [10].

ORBIT FEEDBACK ALGORITHM

The algorithm is essentially a least square fit with the goal to compensate the 10 Hz orbit oscillation by fast correctors [11]. On the left side of Eq. (1), the x_i is the measured beam positions. The x_{ig} is the goal beam position, which is the measured average position in our case.

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} x_{1g} - x_1 \\ x_{2g} - x_2 \\ \vdots \\ x_{mg} - x_m \end{pmatrix} = \begin{pmatrix} x_{1g} \\ x_{2g} \\ \vdots \\ x_{mg} \end{pmatrix} \tag{1}$$

To compensate the oscillation, one needs to introduce orbit offsets by assigning proper correction strength to correctors. The $m \times n$ matrix R denotes the response of the beam positions to the strength of correctors. The proper corrector

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settings can be calculated by solving Eq. (2).

$$\begin{pmatrix} x_{1g} - x_1 \\ x_{2g} - x_2 \\ \vdots \\ x_{mg} - x_m \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{pmatrix} * \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{pmatrix} \quad (2)$$

The Singular Value Decomposition (SVD) [12] method was employed for solving Eq. (2). The response matrix was decomposed to three matrices, $R = USV^T$. U is an $m \times m$ unitary matrix, S is an $m \times n$ rectangular diagonal matrix with eigenvalues on the diagonal in descending order, and V is an $n \times n$ unitary matrix. The inversion of the matrix R can be expressed as $VS^{-1}U^T$. In some cases, one needs to discard small eigenvalues to avoid amplification of beam position and corrector strength errors in the system for better performance. This is called eigenvalue cut. An alternative way of manipulation of the eigenvalues is Tikhonov regulation [13],

$$s = s + a^2/s \quad (3)$$

here s is the eigenvalue, and a is a constant with a value between the largest and smallest eigenvalue.

OPTIMIZATION OF FEEDBACK AT FIXED ENERGIES

The feedback system was first tested in 2010 with 4 correctors and 8 BPMs in the two experimental areas. The best performance was achieved by keeping 2 out of 4 eigenvalues. The full feedback system was tested and implemented operational in 2011.

A number of studies was performed to optimize the system performance. The dependence of performance on the number of BPMs was studied. We kept all 36 BPMs in one case, all 24 triplets BPMs in the other case and only 12 BPMs near Q1 for the last case. The 10 Hz oscillation spectral intensity pattern was different in the first case as shown in Fig. 1.

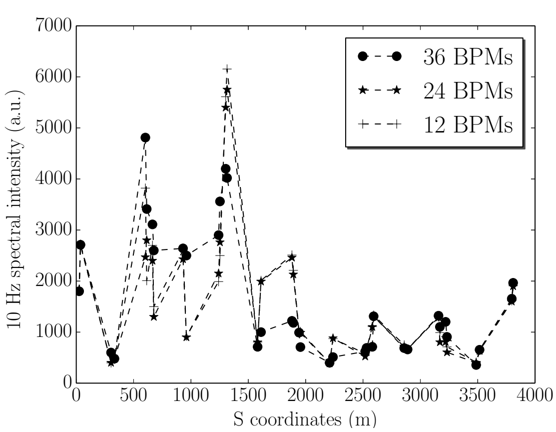

Figure 1: The spectral intensity of 10 Hz oscillation at BPM locations with the global orbit feedback engaged for the case of 36, 24 and 12 BPMs included in the system.

In the exception-handling test, the yo4-b3 BPM was disabled. The system was tested with and without proper adjustment of the matrices due to the missing BPM. The 10 Hz oscillation spectral intensity for both cases are shown in

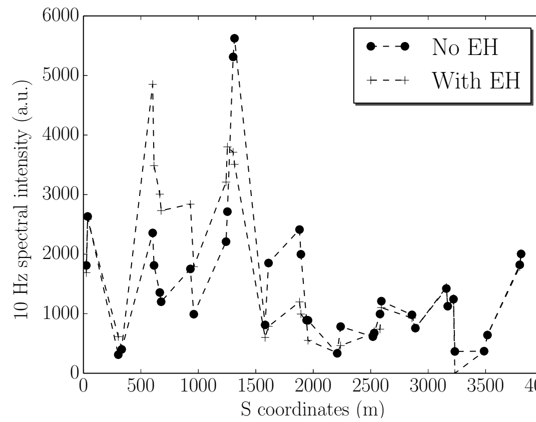

Figure 2: The spectral intensity of 10 Hz oscillation at BPM locations with one BPM excluded from the system, the case without exception handling shown in dots and the case with exception handling shown in plus signs.

Due to optics errors, the model response matrix deviates from the one of the real machine. The response matrix was measured and applied in the feedback. The comparison of the feedback performance with model and measured response matrix was presented in [11].

The feedback was engaged with various eigenvalue cut configuration, and the best performance was found with keeping 6 or 7 eigenvalues. The 10 Hz spectral intensity at all BPMs is shown in Fig. 3.

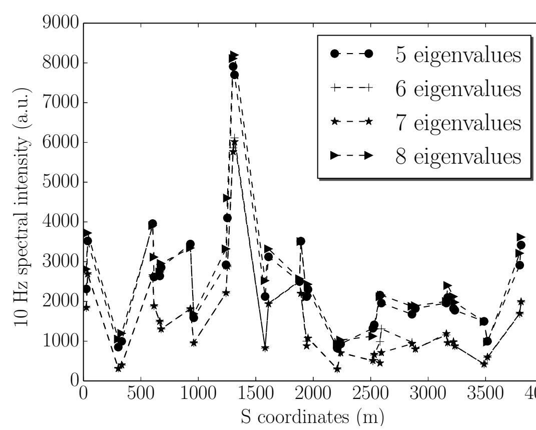

Figure 3: The spectral intensity of 10 Hz oscillation at BPM locations for the case of 5, 6, 7 and 8 eigenvalues are kept in the matrix manipulation.

OPTIMIZATION OF FEEDBACK DURING ACCELERATION

The global orbit feedback during acceleration is complicated by the fact that the change of optics due to beta-squeeze over the course of acceleration. Therefore, the configuration

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of the system during acceleration are different in several aspects with respect to those for fixed energies. The response matrix needs to be updated for the feedback system during acceleration, therefore, ~ 300 matrices were generated for one acceleration cycle based on design optics. These matrices were loaded at 1 Hz rate starting from the beginning of acceleration. A scale factor which is proportional to the beam rigidity was updated at 1 Hz rate as well. Experimental studies showed keeping 6 eigenvalues was the optimal for injection and store energies, therefore, the same technique was applied to all matrices for intermediate energies during acceleration. The global orbit feedback was turned off momentarily for transition crossing event due to the large optics errors [14]. The recorded peak-to-peak beam positions was shown in Fig. 4 for the case with and without feedback during acceleration. The currents of the correctors are shown in Fig. 5.

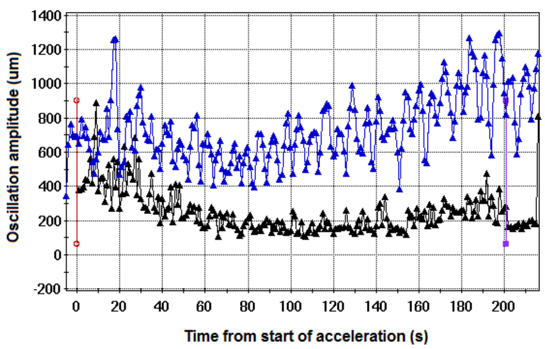

Figure 4: The peak-to-peak amplitude of 10 Hz oscillation during acceleration with and without the global orbit feedback engaged.

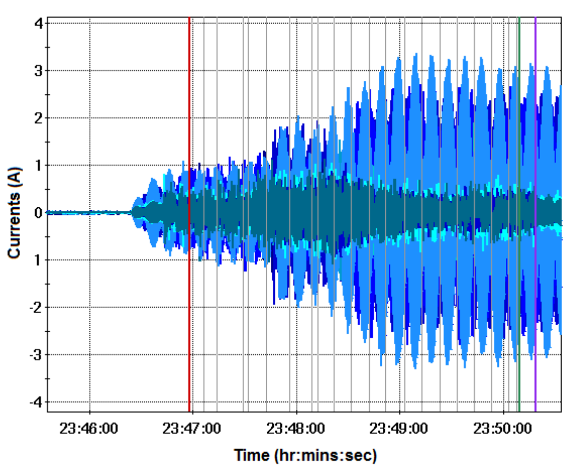

Figure 5: The currents of the correctors during acceleration when the system was engaged..

The system has performed well at injection, during acceleration and over the course of physics stores with keeping 6 eigenvalues until 2015. During the polarized proton program, large amplitude oscillation (Fig. 6) and transients of corrector currents (Fig. 7) were observed with feedback on during acceleration. The test was done to keep 5 eigenvalues only in order to reduce the current of correctors, however, the transients were less but not gone.

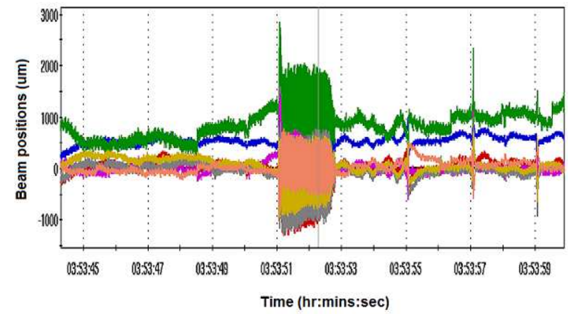

Figure 6: The excitation of oscillation during acceleration observed with polarized proton lattice with global orbit feedback engaged.

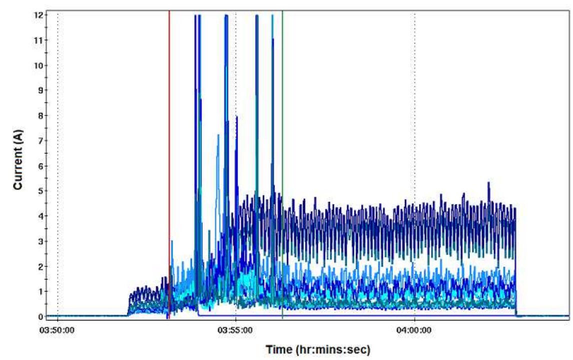

Figure 7: The observed transients of corrector currents during acceleration with polarized proton lattice.

A group of matrix elements were calculated for the case of keeping 6 eigenvalues. The values during acceleration for the polarized proton lattice was shown in Fig. 8. Transients of the currents of correctors were observed to be associated with the sudden changes of matrix elements during acceleration. Therefore, Tikhonov regulation was adopted to smooth the matrix elements during acceleration. With $a = 40$, the same group of matrix elements are shown in Fig. 9. The matrix elements are smoothed to a large extent, however, there were still transients of corrector currents left in the test. With $a = 100$, the same group of matrix elements are shown in Fig. 10. The transients were completely gone with the further smoothed matrix during acceleration. In addition to the smooth behaviour of the matrix elements, the amplitude of the elements were scaled down as well.

In the last test, a high-pass filter which subtracts the DC positions was applied at the same time [15]. With matrix smoothing and the high-pass filter, the system worked without any transients of corrector current. In a later test, the matrices were reverted to the ones with 6 eigenvalue cuts while keeping the filter, the transients still exist however less during acceleration. This means both the matrix smoothing technique and the high-pass filter helped solving the problem.

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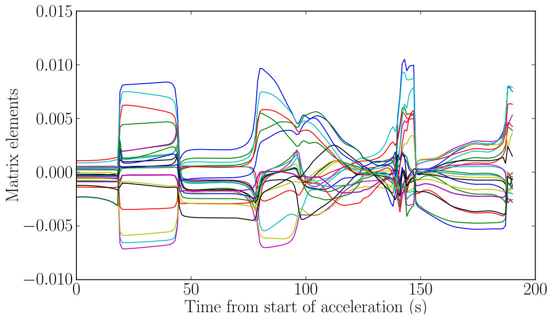

Figure 8: The evolution of selected matrix elements during acceleration with 6 of the 12 eigenvalues kept for the inverted matrix.

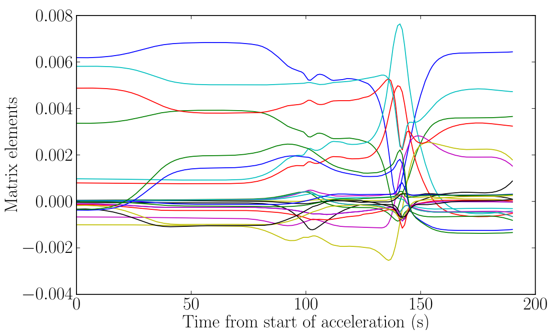

Figure 9: The evolution of selected matrix elements during acceleration with Tikhonov regulation for the inverted matrix with a constant of 40.

SUMMARY

The 10 Hz global orbit feedback system was first optimized at fixed energies at RHIC. The response matrix was measured; only 6 of the 12 eigenvalues were kept in the matrix manipulation to reduce the noise contribution from correctors; and the 24 BPMs near the triplets were used in the system for better suppression of oscillation around experiments. The same configurations were used for the feedback during acceleration. The corrector current transients with the polarized proton lattice was observed. It was found to be related to the steps of the inverted matrix elements during acceleration. The Tikhonov regulation for the inverted matrix was applied to smooth the matrix element during acceleration. The constant of 100 for Tikhonov was chosen to smooth and decrease the matrix elements so that the transients were eliminated. At the same time, a high-pass filter was applied in the system to exclude the contribution of static beam offsets.

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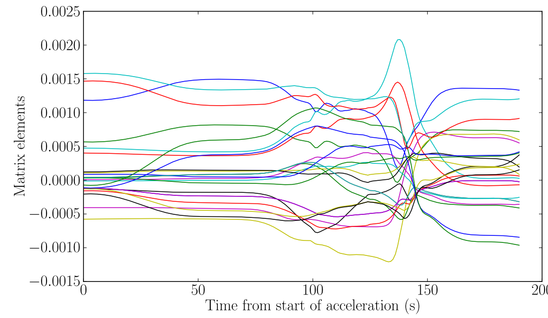

Figure 10: The evolution of selected matrix elements during acceleration with Tikhonov regulation for the inverted matrix with a constant of 100.

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