GLOBAL ORBIT FEEDBACK AT RHIC

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Abstract

For improved reproducibility of good operating conditions and ramp commissioning efficiency, new dual-plane slow orbit feedback during the energy ramp was implemented during run-10 in the Relativistic Heavy Ion Collider (RHIC). The orbit feedback is based on steering the measured orbit, after subtraction of the dispersive component, to either a design orbit or to a previously saved reference orbit. Using multiple correctors and beam position monitors, an SVD-based algorithm is used for determination of the applied corrections. The online model is used as a basis for matrix computations. In this report we describe the feedback design, review the changes made to realize its implementation, and assess system performance.

INTRODUCTION

RHIC consists of two independent superconducting accelerators and operates over a wide range of parameters for colliding intense beams of polarized protons or heavy ions [1]. The physics program often requires changes in particle species and/or beam energies. In the interest of improving overall accelerator availability and providing more stable, reproducible and optimal beam conditions, a global orbit feedback system has been developed and implemented at RHIC during run-10.

The new feedback system [2] targets three specific areas: (1) improved ramp development efficiency when commissioning with new particle species, energies, and/or accelerator optics, (2) precision orbit control during the ramp to high energies, and (3) orbit control and orbit reproducibility during the physics store at fixed beam energies. The latter two areas are of particular interest with regards to preservation of polarization which is vulnerable to diurnal variations in the beam orbits. An example of what feedback should better control is shown in Fig. 1 where the variation in root mean square (rms) of the measured vertical orbit is plotted for 5 different energy ramps within a 24 hour period as measured during run-9. The feedback system should also maintain constant beam trajectories at store both in the interest of polarization preservation and to ensure maximum dynamic range for future fast orbit feedback [3].

FEEDBACK DESIGN OVERVIEW

The new feedback system uses as input position measurements from up to 147 position monitors (BPMs) per plane per ring. The reference orbit to which the beam is to be steered may be either a design orbit (flat except

where intentional bumps are applied, to separate the beams at the non-colliding interaction regions, for example) or a "golden orbit" which is a previously acquired orbit. Subtracted from the measured difference orbit (present minus reference) is the dispersive contribution to the orbit. The corrections are calculated using an SVD algorithm, which leverages off the overconstraint of the system, and the online model for the beam optics. These are distributed to about 115 corrector dipoles per plane per ring. The system operates at the target rate of 1 Hz and was developed entirely using existing infrastructure.
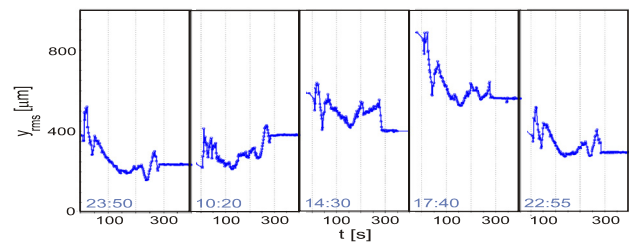

Figure 1: Measured vertical orbit rms versus time during the energy ramp measured at the indicated times.

SUBSYSTEMS

Beam position monitors (BPMs)

The feedback system uses existing stripline monitors and data processing electronics. The precision of each position reading is ~10 μm as recently improved by nearly an order of magnitude by implementation of a new processing algorithm in run-9 [4] for improved determination of the average orbit.

BPM offsets

The corrections for BPM alignment offsets, as obtained from survey data, were critically reviewed prior to run-10. A few accounts of double-implementation were found and corrected. More importantly it was discovered that the sign of the corrections had been applied incorrectly many years ago. Additionally, the orientation of the so-called "QCS package" (lumped quadrupole, corrector, and sextupole) had not been taken into account which affected about 25% of the BPMs. These issues were addressed and corrected.

Conversion of reference orbits

As part of the feedback design effort, software infrastructure was developed to allow target orbits to be specified in terms of either the desired position or a previously measured position at each BPM. (In the past, "orbits" were specified and saved by recording corrector

strengths). This improvement allows more intuitive oversight and reduces the likelihood of human error.

BPM data delivery

Prior to run-10 the BPMs nominally delivered data at a 0.5 Hz rate, however, as it turned out, often non-deterministically. Shown in Fig. 2 are the BPM acquisition rates as measured under nominal conditions before and after changes to the BPM FEC code. Before the changes, a large fraction of BPMs delivered data late by up to 3.5 s. After the changes the average rate was reduced to 150 ms with a few "fliers" which were removed by changes to the BPM ADO code. During run-10 other more subtle data delivery issues were addressed including for example occasions of transmission of 1000-second old "stale data".
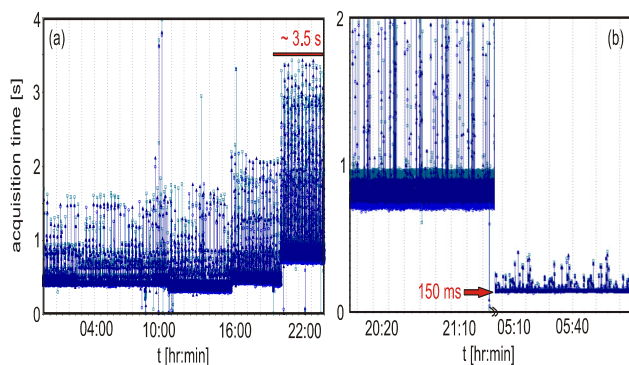

Figure 2: Average BPM data acquisition rates before (a) and after (b) changes for deterministic delivery rates.

Networking

In response to observed latencies / missing data in run-9 at the start of the energy ramp and the anticipated increase in data transfers from new systems (stochastic cooling and low-level rf) in run-10, 1 Gb/s links were added between all service buildings and the central RHIC network hub and a 10 Gb/s link from there to the main control room.

Model generation

The matrices containing the energy- and optics-dependent BPM-to-corrector response functions are derived using machine optical functions, calculated from the online model. Previously these were specified at only 20-30 locations depending on ramp duration, at the so-called "stones". For continuous orbit these are now generated for every second along the energy ramp by interpolation between stones. The computation time required is considerable with 150 BPMs times 120 correctors → 180000 matrix elements times 4 planes (horizontal and vertical in each accelerator) → 72000 elements computed at each of 400 seconds ~30 million values for a ramp of 400 s duration). To ensure fast turn-around between new optics design and implementation on the accelerators, significant coding work was performed to allow parallel processing for this matrix generation and for optimizing the processing techniques.

SVD algorithm

The SVD algorithm was developed previously for routine use at injection, at the "stones" (using feed-forward of corrections derived from evaluation of a previous ramp), and used periodically (every 30 minutes) at store energy. As part of the algorithm, the dispersive contribution, as determined using the model dispersion function and BPMs in the collider arcs, is subtracted from the measured orbit. A user-selectable cut on minimum value of the eigenvalue is used to limit the number of significant eigenvalues employed in the computations. If the number of available BPMs changes (due to a bad status as detected by a status bit), the SVD matrices are appropriately reconfigured and implemented between successive applications (at up to a 1 Hz rate). Total computation time including this exception handling was measured to be less than 250 ms.

Distribution of corrections / corrector control

The corrections are multiplied by a user-selectable gain factor then distributed on the RHIC real-time data link to the wave form generator (WFG) managers. These were modified to deliver the corrections to the WFGs at a 720 Hz rate thus effectively ramping in the corrections. The WFGs were programmed to sum the existing corrector setpoint values with the newly acquired corrections. The sums are then sent to the power supplies for the corrector magnets. The time required to distribute and apply corrections was measured to be <150 ms.

Exception handling

For orbit feedback extensive use was made of the modifications developed during run-9 to extend the self-check diagnostic capabilities of the BPM hardware.

The requested corrector values are also checked to ensure that the currents and requested ramp rates do not exceed user-specified limits. During commissioning these exceptions were modified to take into account the changing beam rigidity.

Other features

Invaluable to the fast commissioning process (of this feedback as well as other feedback loops under operation and development such as tune/coupling feedback and chromaticity feedback) were the added abilities (1) to revert easily back to the initial state prior to engaging feedback and (2) to feed-forward corrections acquired on a ramp with feedback for use on a subsequent ramp.

COMMISSIONING EXPERIENCE

First tests were performed at injection energy for which the accelerator optics is static. Using multiple (>10) correctors per plane, the orbits were intentionally distorted and then orbit feedback was engaged. In Fig. 3 are shown the root-mean-square (rms) of all BPM data acquired in the accelerator arcs as a function of time illustrating convergence of the feedback algorithm. The rate of convergence was measured and found to scale as

expected with feedback gain. While convergence was clearly demonstrated in both rings, initial tests in one ring were repeatedly accompanied by elevated beam loss. This was eventually traced to an unfortunate database misconfiguration of a single BPM (a BPM nominally used only at injection located in the dump line was configured as being located at a final focussing triplet magnet with many thousand meter beta function). Once this error was revealed, feedback reliably converged without accompanying beam loss.
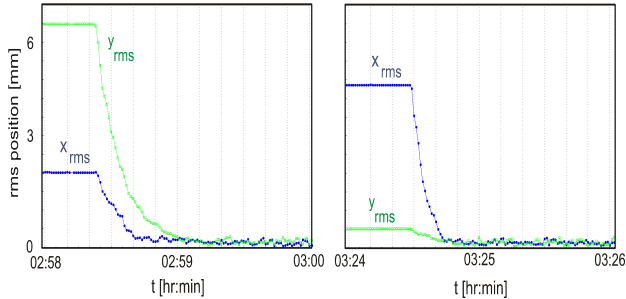

Figure 3: Measured orbit rms in both RHIC accelerators in the horizontal (x) and vertical (y) planes as global orbit feedback was engaged in each ring.

A comparison of the measured vertical orbit rms from 4 consecutive energy ramps is shown in Fig. 4. The horizontal axis represents time (in seconds) with time t=0 corresponding to the start of the ramp. The first two ramps (pink and red traces) exhibited the offsets characteristic of diurnal fluctuations. The second two ramps (blue and green) show first fast convergence when feedback was engaged (at t<0), then continuously improving orbit rms throughout the energy ramp (which in this case was executed with a 10% gain). The reproducibility between successive ramps with continuous orbit feedback is very good.
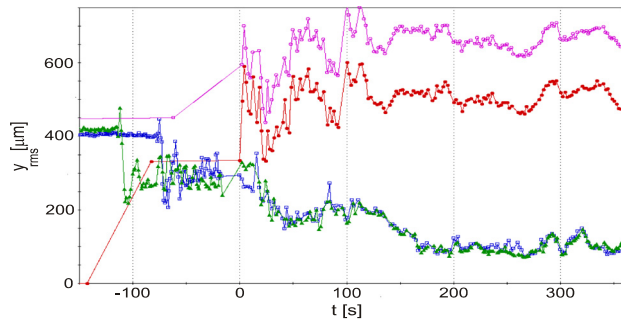

Figure 4: Vertical orbit rms during energy ramp measured with (blue, green) and without (red, pink) global orbit feedback versus time.

Application of feed-forward of orbit corrections has also been demonstrated. Shown in Fig. 5 are the change in corrector strengths in the horizontal (top) and vertical (bottom) planes during the energy ramp. The data on the left were acquired during the first ramp with orbit feedback. On the right, the data were acquired again with feedback after implementing the corrector currents just recorded previously.
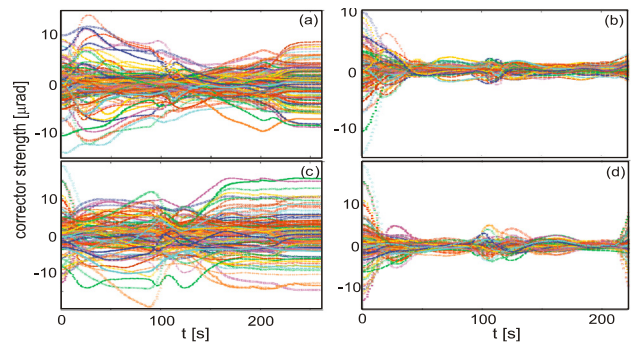

Figure 5: Horizontal (a,b) and vertical (c,d) corrector strengths during orbit feedback before (left) and after one iteration of feed-forward (right).

To combat the effects of diurnal variations on accelerator performance, an automated procedure has been used in the past to steer the orbit once every ~30 minutes. As a test, the new feedback was engaged during normal operations as shown in Fig. 6 where the vertical orbit rms was seen to change rapidly (with outside temperature). The large step change corresponds to first steering to the orbit saved previously then engaging the new orbit feedback which was then left on for an extended period of time showing its ability to combat the diurnal variations.
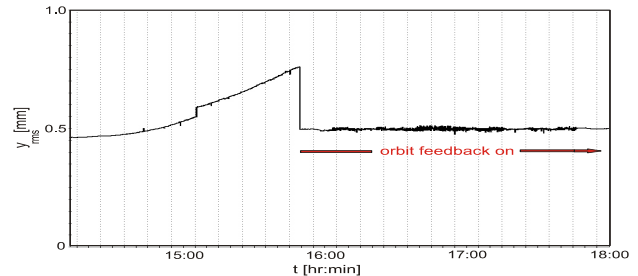

Figure 6: Measured vertical orbit rms versus time without feedback evidencing drift, then with feedback engaged.

SUMMARY

Continuous orbit feedback along the energy ramp was developed and successfully demonstrated in run-10 at RHIC. The initiative led to other improvements such as identification of BPM survey offset errors and conversion to BPM-based orbit references. Future developments will include continuous application at full energies and parallel operation with tune/coupling [5], and chromaticity [6] feedback.

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