SUMMARY OF COUPLING AND TUNE FEEDBACK RESULTS DURING RHIC RUN 6, AND POSSIBLE IMPLICATIONS FOR LHC COMMISSIONING*

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Abstract

Early efforts [1] to implement tune feedback during the acceleration ramp in RHIC were hampered by large betatron coupling, as well as the requirement for large dynamic range. Both problems have been addressed, the first by implementation of continuous measurement of coupling, and the second by the development of an improved analog front end. With these improvements, simultaneous coupling and tune feedback were successfully implemented for acceleration ramp development during RHIC Run 6. During the course of this work it became clear that direct excitation of the betatron resonances by high harmonics of the 60Hz power frequency was an obstacle to making the system fully operational. We report here on these results from RHIC Run 6, and implications for LHC commissioning.

INTRODUCTION

In hadron accelerators, to minimize emittance growth and reduction in luminosity available to the physics experiments, the beam excitation needed to reliably operate phase-locked loop (PLL) tune measurement systems must be very small. The power in the resulting betatron signal is typically of the order of femtowatts, while the power delivered to the pickup unrelated to the betatron tune is of the order of watts. In addition, at RHIC transition crossing introduces further dynamic range requirements. Much effort was devoted to solving this problem, which was ultimately dealt with by the Direct Diode Detection [2] Analog Front End (3D AFE).

PLL tune tracking and feedback become impossible as coupling becomes large. Coupling rotates the planes of betatron oscillation (the eigenmodes) away from the plane in which the magnet portion of the tune feedback loop applies corrections. When this rotation approaches 45 degrees the magnet loop applies corrections in the wrong plane and the feedback is driven unstable. To deal with this, the PLL was reconfigured to measure both eigenmode projections in both planes, making possible continuous coupling measurement, and eventually feedback. The architecture of the system developed to accomplish this for RHIC Run 6 is shown in Figure 1.

Analog processing of signals from the pickup is accomplished by the 3D AFE. After detection, filtering, and amplification the tune signals from the two pickup planes are split and digitized.

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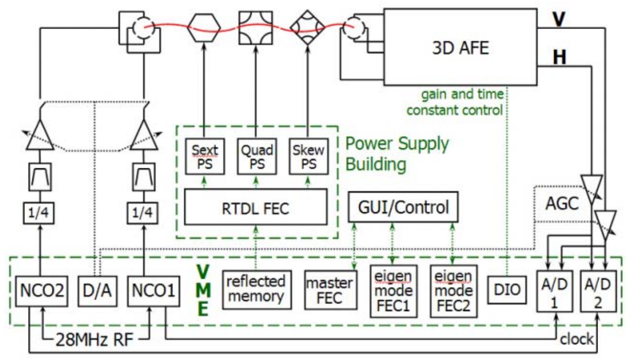

Figure 1: System Block Diagram

Processing is accomplished in two signal paths that, except for the coupling correction, are independent. The two paths provide the data needed to maintain lock to the two eigenmodes, and to correct coupling and tune.

COUPLING FEEDBACK

Figure 2 shows the eigenmodes and their projections [3]. The left portion shows the special case when the minor axes of the ellipses vanish, while the right shows the more general case where a coupling phase is also present. The frequency of mode 1 is denoted by Q_1, while $A_{1,x}$ and $A_{1,y}$ represent the amplitudes of this mode in the horizontal and vertical plane respectively. Similarly $\phi_{1,x}$ and $\phi_{1,y}$ represent the phases of this mode in the horizontal and vertical plane respectively. The same notation applies for mode 2.

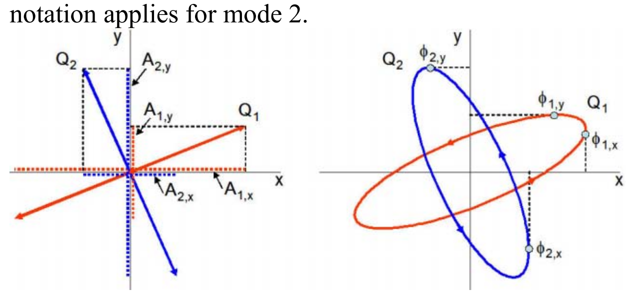

Figure 2: Coupled eigenmodes and their projections

All of the quantities shown in the figure are measured by the PLL. From these quantities the following parameters can be calculated:

$$r_1 = \frac{A_{1,y}}{A_{1,x}} = \sqrt{\frac{\beta_y}{\beta_x}} \cdot \frac{|C^-|}{2\nu + \Delta}, \quad r_2 = \frac{A_{2,x}}{A_{2,y}} = \sqrt{\frac{\beta_x}{\beta_y}} \cdot \frac{|C^-|}{2\nu + \Delta},$$

$$d\phi_1 = \phi_{1,y} - \phi_{1,x}, \quad d\phi_2 = \phi_{2,x} - \phi_{2,y}$$

where β_x and β_y are the horizontal and vertical beta functions at the pickup, and

$$\nu = \frac{1}{2}\sqrt{\Delta^2 + \left|C^-\right|^2},$$

$$\left|C^-\right| = \frac{2\sqrt{r_1 r_2}\,\left|Q_1 - Q_2\right|}{(1 + r_1 r_2)}, \quad \Delta = \frac{\left|Q_1 - Q_2\right|(1 - r_1 r_2)}{(1 + r_1 r_2)}$$

The coupling amplitude C^- is often referred to as dQ_{min}, or the minimum tune split. The parameter Δ is the difference between the fractional parts of the unperturbed, or 'set' tunes. When the eigenmodes are decoupled the eigentunes (measured) and the unperturbed (set) tunes are identical. The unperturbed tunes can be calculated by:

$$Q_{x,0} = Q_1 + \tfrac{1}{2}\Delta - \tfrac{1}{2}\sqrt{\Delta^2 + \left|C^-\right|^2},$$

$$Q_{y,0} = Q_2 - \tfrac{1}{2}\Delta + \tfrac{1}{2}\sqrt{\Delta^2 + \left|C^-\right|^2}$$

Figure 3 shows data from a ramp during RHIC Run 5.

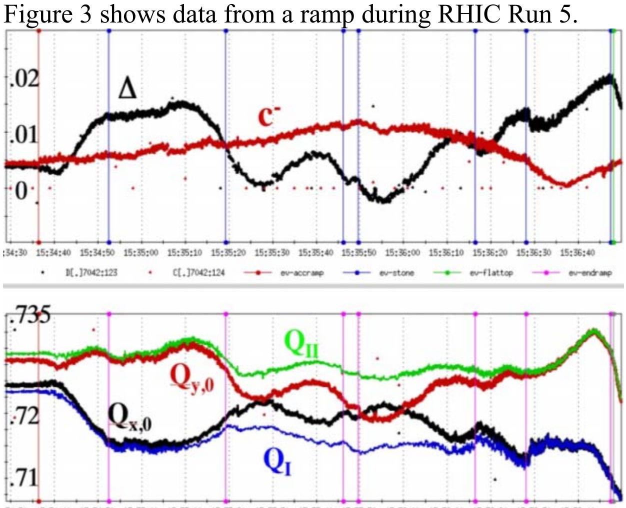

Figure 3: Measured eigentunes, and calculated set tunes and coupling parameters

The coupling parameters C^- and Δ are shown in the upper pane. The lower pane clearly shows crossing of the set tunes. If tune feedback had been on, the feedback would have been driven unstable by the set tune crossing.

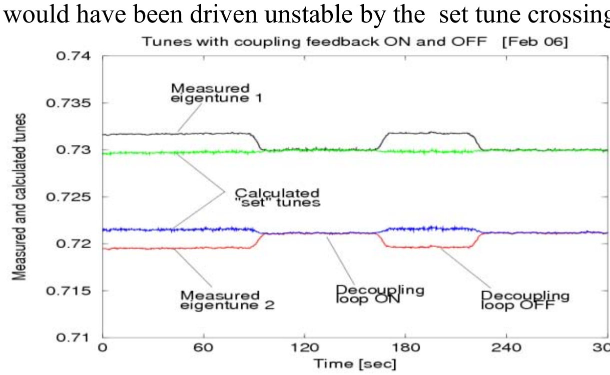

Figure 4: Coupling feedback at injection

With the availability of continuous coupling measurement, coupling feedback was implemented [4]. Figure 4 shows set and measured tunes as the coupling feedback loop is turned on, then off, and then back on again. With the loop off the measured tunes are driven apart by the coupling. With the loop on the set and measured tunes are essentially the same.

TUNE FEEDBACK

Decoupling is a pre-requisite for tune feedback. With coupling feedback available, the acceleration ramps during RHIC Run 6 were commissioned with simultaneous tune and coupling feedback. Figure 5 shows tune data from a ramp late in the commissioning period.

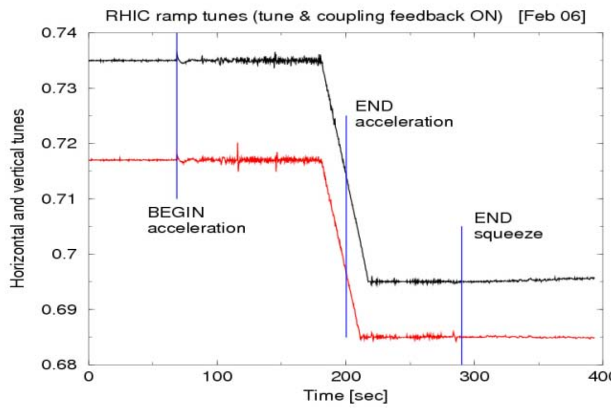

Figure 5: Eigentunes during an acceleration ramp with tune and coupling feedback enabled

While the initial feedback efforts were nominally successful and clearly demonstrated the viability of coupling feedback, and hence enhanced robustness of tune feedback, plans to bring the system to operational status were derailed by the intermittent appearance of 'noise' in the PLL during ramping. Many possible sources of this noise were investigated, and it was eventually concluded that the primary source was direct excitation of the betatron resonance by high harmonics of the power line frequency [5], multiples of 60Hz in the case of RHIC.

MAINS HARMONICS

The 3D AFE delivers significant improvement in position measurement sensitivity, with estimated 10nm resolution at RHIC. This AFE has been installed at the CERN PS and SPS, at the FNAL Tevatron, and at RHIC. Mains harmonics have been observed at every installation. The source of these harmonics has been hotly debated. Measurements at RHIC suggest that these harmonics have their origin in the main dipole power supplies. There are three primary measurements that point towards this conclusion.

Ramping and Store Power Supplies

There are two power supplies for the RHIC dipoles, a 30V/5500A 'hold' supply for injection and store, and an additional 400V/5500A supply that is switched in to provide the field time derivative needed for ramping. Figure 6 shows the beam spectrum in the vicinity of the betatron line during tune tracking of a 31GeV ramp of polarized protons in RHIC Run 6, as seen by the 3D AFE.

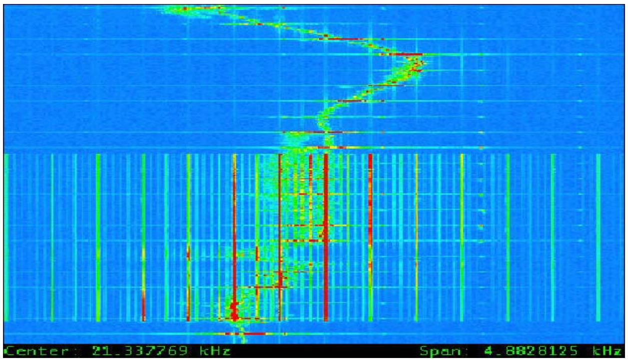

Figure 6: Spectrogram during ramping

The vertical axis spans ~50 seconds, with the most recent time at the bottom. The onset of strong 60Hz harmonics about 20 seconds into the ramp coincides with the turning on of the ramping power supplies, and the end of the harmonics with their turning off. The harmonics have a pattern that repeats every 720Hz, with strong lines spaced by 360Hz. The time correlation suggests that the source of strong mains harmonics during ramping is the ramping power supply. During ramping the strongest mains harmonics are ~80dB above the 3D AFE noise floor. With only the ‘hold’ supply they are ~40dB above the noise floor. The effect of the mains harmonics on the quality of the tune tracking is evident.

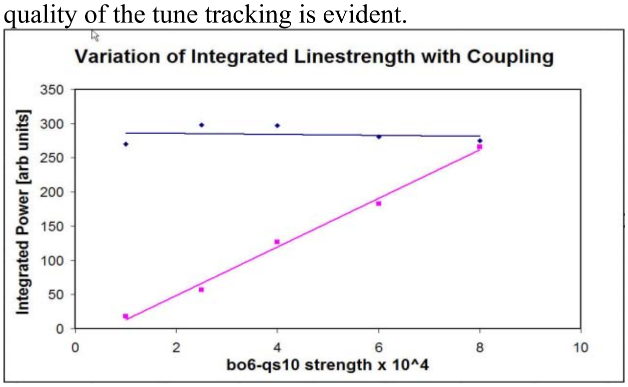

Figure 7: Harmonic power during skew scan

Coupling

Motivated by the Tevatron observation that the spectrum was altered by the coupling introduced by the separation helix, a single RHIC skew quad was scanned from zero to ~10^{-3} m^{-2}. The result is shown in Figure 7. Mains harmonics power in the horizontal plane is uncorrelated with coupling strength, and strongly correlated in the vertical plane. This conclusively demonstrates that the mains harmonics are on the beam, and further that the excitation is in the horizontal plane.

Power Supply Balancing

In the most recent measurement, we monitored the beam spectrum at injection while changing timing of one of the phases of the 12 phase main dipole ‘hold’ supply. In Figure 8 the spectra at 755am and 817am are baseline spectra, and the 810am spectrum results from a timing change. The spectral variation with the timing change is clear.

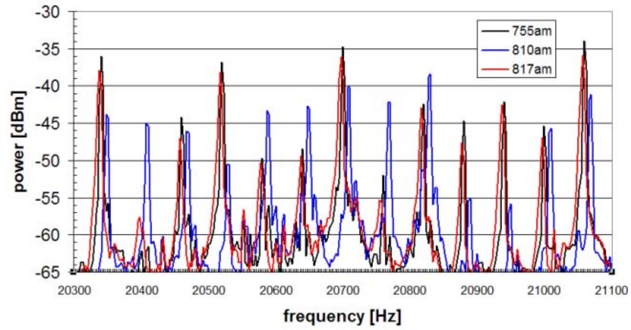

Figure 8: Baseline and tweaked specta

The timing change required to produce this spectral change was large. Measurements were made with many different timings. The total spectral power remained constant during these changes, even though the spectral pattern changed. Our preliminary conclusion from these measurements is that, while there is an observed causal relationship between power supply balancing and spectral content, it is unlikely that improved balancing will significantly reduce the mains harmonics. We continue to investigate other possibilities.

LHC IMPLICATIONS

The success of simultaneous tune and coupling feedback in RHIC greatly improves the possibility that robust feedbacks can be implemented in the LHC.

We emphasize that mains harmonics in RHIC are anomalously large, and their origin is not understood. This has two implications for the LHC. First, they have prevented further system refinement, as well as obstructing development work on chromaticity measurement and feedback. And second, until their origin is understood the possibility cannot be fully eliminated that a similar difficulty might arise in the LHC. Resolution of this problem is our highest priority.

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