



**BNL-77664-2007-CP**

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measurement and feedback during RHIC run 7***

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*Presented at the 22<sup>nd</sup> Particle Accelerator Conference (PAC)  
Albuquerque, New Mexico  
June 25 – 29, 2007*

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# PROGRESS IN TUNE, COUPLING, AND CHROMATICITY MEASUREMENT AND FEEDBACK DURING RHIC RUN 7\*

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## ANOMALOUS BEAM RESPONSE

Figure 1 is an FFT in the vicinity of the vertical betatron resonance in one of the two RHIC rings, typical of what is seen in both planes of both rings. There was no deliberate beam excitation. The tunes were decoupled and separated.

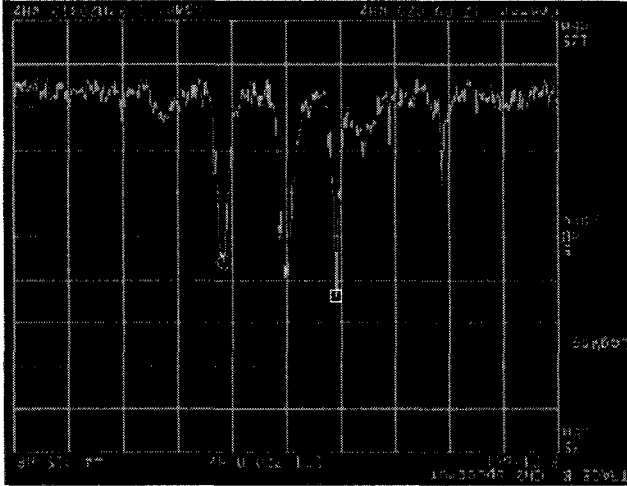


Figure 1. Unexcited betatron spectrum at injection

Four sharp peaks are visible in the image, as well as two smaller broad peaks. The spacing of the peaks is irregular, and cannot be correlated with either the synchrotron or power line frequencies. Neither chromaticity nor RF voltage changes had a significant effect on the appearance.

The most central peak was generally the most favorable for locking. The tracker would auto-lock on the first peak it found, which inevitably was not the central peak, and would have to be manually and laboriously teased onto the proper line.

At times there was what seemed to be an unpredictable relation between which line was acquired and the phase of the coupling measurement relative to the skew quad correction families. Sometimes the coupling feedback loop would be unstable when closed at injection, and the beam would be lost. Upon refilling and reacquiring lock on a different line the coupling loop would be stable.

This behavior was not seen during Run 6 with polarized protons, or in earlier runs with ions. However, this was the first ion run in which the baseband tune tracker was used. Earlier ion runs used the 245MHz tune tracker, which was above the coherent spectrum at injection, and may explain why this beam response had not been previously seen. There is some speculation that the observed anomalous beam response results from the low injection energy for

\*Work supported by US Department of Energy

Abstract

Tune feedback was first implemented in RHIC in 2002, as a specialist activity. The transition of the tune feedback system to full operational status was impeded by dynamic range problems, as well as by overall loop instabilities driven by large coupling. The dynamic range problem was solved by the CERN development of the Direct Diode Detection Analog Front End [1]. Continuous measurement of all projections of the betatron eigenmodes made possible the world's first implementation of coupling feedback during beam acceleration [2,3], resolving the problem of overall loop instabilities. Simultaneous tune and coupling feedbacks were utilized as specialist activities for ramp development during the 2006 RHIC run. At the beginning of the 2007 RHIC run there remained two obstacles to making these feedbacks fully operational in RHIC - chromaticity measurement and control, and the presence of strong harmonics of the power line frequency in the betatron spectrum [4]. We report on progress in tune, coupling, and chromaticity measurement and feedback, and discuss the relevance of our results to LHC commissioning.

## INTRODUCTION

The RHIC Tune Feedback system and results with proton beams from Run 6 are described in detail elsewhere [5]. The focus of this paper is on unexpected difficulties encountered during the ongoing Run 7. In the abstract we asserted that there remained two obstacles to making the feedbacks operational, namely mains harmonics and chromaticity control. While the experience with gold beams during Run 7 has shown that this is still true, two new phenomena have revealed themselves.

The first is an anomalous betatron resonance shape, which exists only at injection and very early in the acceleration ramp. This phenomenon considerably complicates the task of acquiring a reliable phase lock to the resonance, and additionally has impeded the effort to implement chromaticity feedback. However, it has had only minimal effect on the effort to commission ramps with tune and coupling feedback.

The second is a phenomenon that we call 'tune scalloping'. It results from the combined effects of three causes - the large kicker excitation needed for reliable tune tracking in the presence of mains harmonics, improved performance of the tune tracker, and poor chromaticity control. Its effect on ramp development has been more damaging.

ions. At injection many power supplies are close to minimum current, where regulation is poor. As the ramp begins and currents increase the anomalous response diminishes. Additionally, this anomalous response was not seen during beam studies of near-integer working points.

Efforts to tune the PID loop of the tune tracker at injection revealed a discontinuous behavior of tune tracking with small changes in loop parameters. As proportional gain was increased there was a sudden and dramatic improvement in the amplitude and phase signals, and a somewhat smaller improvement in tune tracking. Our understanding is that higher gains prevent jumping between the multiple peaks.

The anomalous beam response at injection may have contributed to the excessive noise that appeared in tune tracking when the tune and coupling feedback loops were closed. In previous years, the additional noise and tune dither resulting from closing the loops was barely perceptible. In the present run the tune dither increased significantly when the loops were closed. This was cause for some concern regarding overall loop stability, but experience suggests that the effect of the large tune dither is minimal for tune and coupling feedback.

Unfortunately, the anomalous beam response is not so benign with regard to chromaticity feedback. The measurement needed for this feedback is accomplished by modulating the beam momentum, and measuring the amplitude of the resulting tune modulation. With tune feedback on the tune modulation is suppressed, and the chromaticity information is extracted from the quadrupole correction strength. The tune modulation places additional demand on the tune tracker. With normal loop gains the tune modulation causes the tracker to be dragged between peaks of the beam response. The combination of the anomalous beam response, noise that appears when the loops are closed, and the additional stress of tune modulation requires exceptionally high loop gains for reliable chromaticity measurement. Tune dither becomes so large that overall loop stability is a real concern.

## TUNE SCALLOPING

During Run 7 we observed a phenomenon that we call 'tune scalloping'. Figure 2 is a typical example.

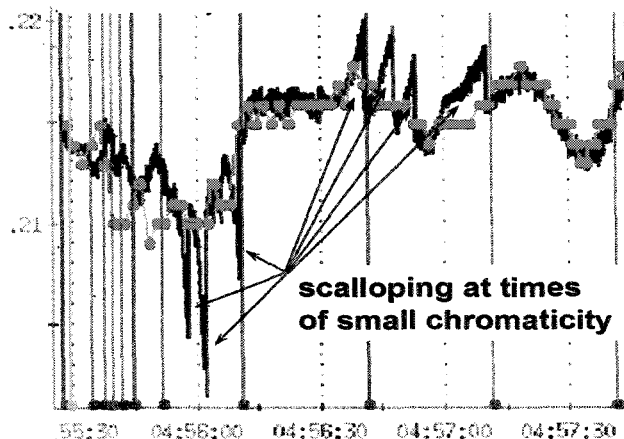


Figure 2. Tune scalloping on the ramp

The red trace is the vertical tune as measured by the tune tracker during a portion of a ramp. The green dots are tune as measured by the conventional kicked tune system. The excursions of the tune tracker measurement are clearly visible.

## Mains Harmonics

In RHIC the betatron resonance is excited by high harmonics of the power line frequency. This excitation is much stronger than in similar large synchrotrons (for instance, the Tevatron or the SPS). During ramping the resulting spectral lines extend as much as 70dB above the noise floor of the tune tracker. Reliable tune tracking requires that kicker excitation be ~100 times stronger than what would be needed without this interference. When we turn down kicker excitation, the scalloping stops.

## Improved Tune Tracker Performance

During Run 6 we tried to filter out the mains harmonics. The resulting large phase shifts limited tune tracker loop gains, without giving satisfactory results. The mains harmonics are simply too large and closely spaced to be effectively filtered. For Run 7 we gave up on this approach and opened up the filter. This permitted much larger loop gains and greatly improved tune tracking. When we turn down loop gains, the scalloping stops.

## Poor Chromaticity Control

The third ingredient in the recipe for tune scalloping is small chromaticity. Our intent had been to commission Run 7 with chromaticity feedback, but the controls infrastructure needed for sextupole control was not ready. Even if it had been ready, the anomalous beam response at injection would have been problematic. Without this feedback, it was not unusual to have small (or even wrong-signed) chromaticity during ramp development.

## The Combined Effect

The combination of excessive kicker excitation, precise tune tracking, and poor chromaticity control results in tune scalloping. The tracker preferentially excites a small subset of the tune distribution, a dot in the middle of phase space. With small chromaticity and large excitation, this subset is driven to large amplitude. It experiences amplitude-dependent tune shift, and the tracker follows it out of the tune distribution, exciting it to progressively larger amplitude and tune deviation, until it starts dribbling out of the dynamic aperture and is depleted. The tracker then falls back to the middle of phase space, grabs another dot and drives it out of the distribution, ...

Figure 3 shows horizontal and vertical tunes and in-phase and quadrature signals during a ramp with feedbacks on. The blue vertical bars in the images are 'stepstones'. In this ramp tune and coupling were being continuously controlled by the feedback loops, but chromaticity was open-loop, being adjusted at the stepstones. In the upper pane, the amplitude of the vertical response takes off at a stepstone shortly before mid-ramp, then begins to oscillate as slices are driven up,

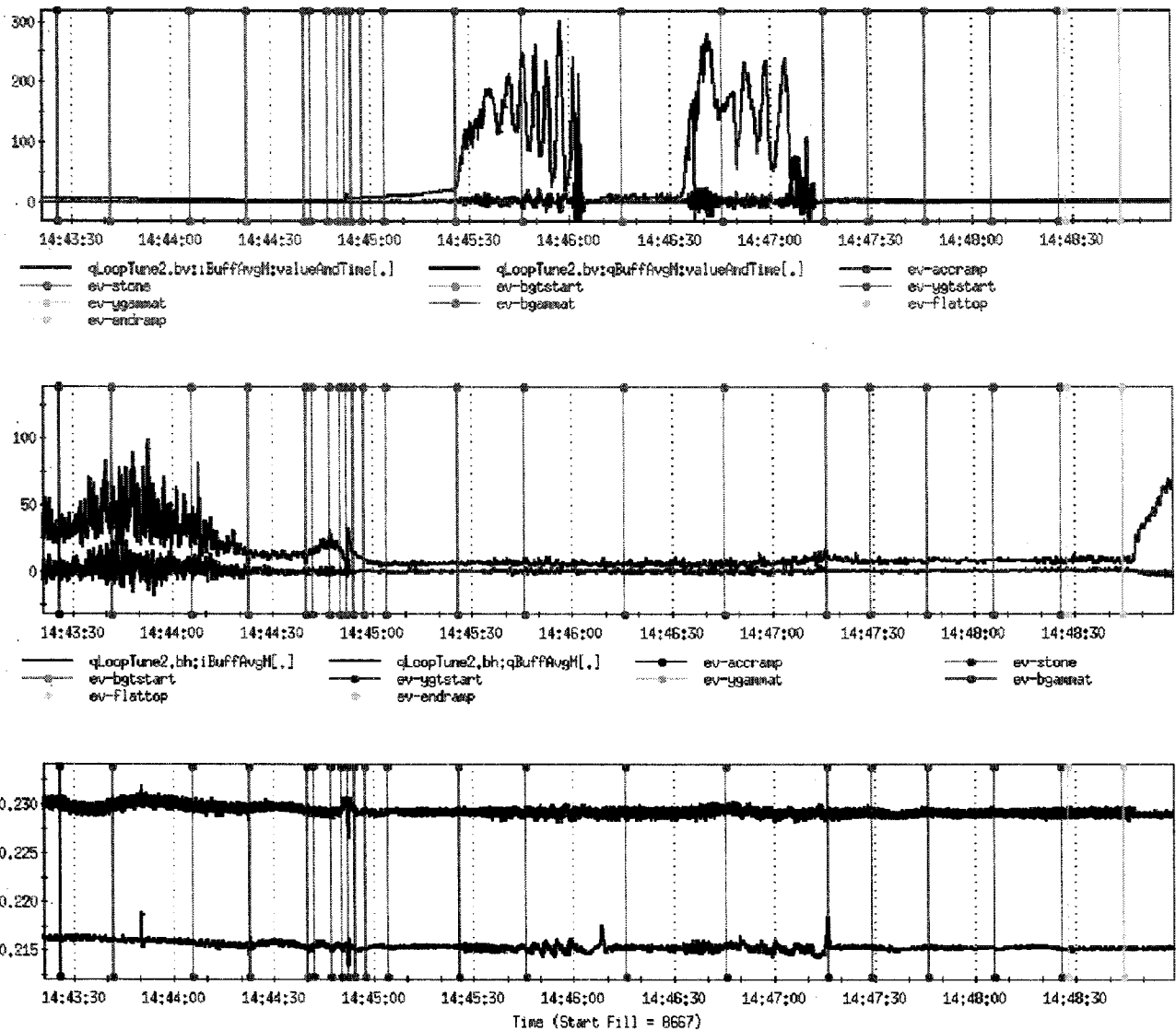


Figure 3. Tune Scalloping during Ramping with Tune and Coupling Feedbacks

depopulated, driven up,... The oscillations stopped when loop gains and kicker excitation were manually lowered. After ~30 sec they were restored to slightly less than their original values, and the oscillations took off again, stopping when gains and excitation were again lowered. The tune fluctuations, despite the effect of the feedback loop, are visible in the tune traces. The quality of the coupling feedback was also affected.

Tune scalloping puts the tune feedback effort in a tight box. It damages operational reliability. Measures to ameliorate the scalloping also damage reliability. The problems of mains harmonics and chromaticity control have found a particularly bothersome way to manifest.

### CONCLUSION

Despite the difficulties outlined here, the tune and coupling feedback effort made a useful contribution to Run 7 ramp development, and has also proven to be an essential tool for machine studies.

The robustness of the tune and coupling feedback in crossing transition bodes well for LHC commissioning.

One of the unexpected problems (tune scalloping) would disappear if the mains harmonics were not so strong. For the other unexpected problem (anomalous beam response at injection), the best candidate explanation so far is again power supply related. If these power supply problems are absent in the LHC, then the field will be clear there to deal with the problem of chromaticity control. This control is also an issue at RHIC, and efforts are ongoing to implement chromaticity feedback.

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