# IMPROVEMENTS FOR OPERATIONAL BASEBAND TUNE AND COUPLING MEASUREMENTS AND FEEDBACK AT RHIC*

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### *Abstract*

Throughout RHIC Run-9 (polarized protons) and Run-10 (gold), numerous modifications to the Baseband Tune (BBQ) system were made. Hardware and software improvements resulted in improved resolution and control, allowing the system to overcome challenges from competing 60Hz mains harmonics, other spectral content, and other beam issues. Test points from the Analog Front End (AFE) were added and connected to diagnostics that allow us to view signals, such as frequency spectra on a Sr785 dynamic signal analyser (DSA), in real time. Also, additional data can now be logged using a National Instruments DAQ (NI-DAQ). Development time using tune feedback to obtain full-energy beams at RHIC has been significantly reduced from many ramps over a few weeks, to just a few ramps over several hours. For many years BBQ was an expert-only system, but the many improvements allowed BBQ to finally be handed over to the Operations Staff for routine control.

## INTRODUCTION

Tune measurement and feedback [1, 2, 3] in RHIC was first begun during the 2004 RHIC gold run as part of the US LHC Accelerator Research Program (LARP). Development of the system has continued since then with the present installation consisting of a pickup and kicker in each of the 1 and 2 o'clock sectors in the RHIC tunnel. The remainder of the system is installed in Service Building 1002A and consists of direct diode detection (3D), and analog front end (AFE), a kicker chassis, various VME/controls modules (such as Numerically Controlled Oscillators (NCO), digitizers, and timing), and several diagnostics packages including Stanford Research Systems Sr785 Dynamic Signal Analyzers and National Instruments PCI-6143S Multifunction DAQ PCI cards.

From the 2004 run through the 2008 run, a good amount of progress was made, but an expert was still required to operate the BBQ system. Various problems were encountered [4] such as mains interference, 'anomalous' beam transfer functions, and 'tune scalloping' which often interfered with acquiring a successful tune lock on the beam. Prototype boards and chassis were fabricated to try to help solve some of these problems.

Prior to the 2009 run (Run-9), a new team of people took over responsibility for BBQ [5]. During this time, nearly 50 issues involving tune measurement hardware items were addressed, along with numerous software enhancements that significantly improved resolution of the measured tunes. Modifications were also made to allow for exploration of near integer working points, as well as working points near 1/3.

## HARDWARE MODIFICATIONS

### *General Modifications for Operations*

Among the first major tasks were massive cleanups of the tunnel areas and Service Building 1002A. Both areas contained a great deal of clutter (old cables, connectors, clamps, etc). A number of old, unused prototype chassis were still installed in the racks, some with cables connected only at one end. Once all of the extraneous equipment was removed, the remaining equipment was adjusted such that the racks for the blue and yellow rings were identical in layout. Blank panels were added to racks as needed to cover up empty areas and improve shielding.

Next, attention was focused on improving the AFEs. Several voltage under-rated capacitors were replaced with properly rated capacitors. Transfer functions of the AFE were simulated and measured, and upon comparison of the results were found to match well. A driver board was added to each AFE to get the pickup +/- signals into the controls system so a dB-to-mm position calculation would be available. The addition of the test signals allow the BBQ pickups to be easily centered on the beam, rather than the beamline.

The most significant effort on the AFE was adding additional test points to observe internal signal levels. Small daughter cards were added to monitor the following signals: +/- input signals from the pickups, the input difference signal, and the filtered signal. All of these signals can be observed via several methods: a local scope, an Sr785 DSA, or the NI-DAQ. Two, 2-channel DSA units are installed, one each for the blue and yellow rings. Typically the difference signals of the blue horizontal (BH), blue vertical (BV), yellow horizontal (YH), and yellow vertical (YV) planes are monitored and logged through the controls system, but signals can be changed locally if necessary. The NI-DAQ system consists of two computers, each with two 8-channel PCI-6143S cards that sample at 250kSamples/second. All four test point signals from each plane (BH, BV, YH, and YV) along with several kicker diagnostic signals are input into the cards. The DAQ is triggered automatically at the start

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of every RHIC ramp and collects five minutes of data. The data is stored in .tdms format which can be read and analyzed using LabVIEW or MATLAB.

As with the AFE, several modifications were made to the kicker amplifiers. A Hall Effect current transducer was added to each output of the kicker amps, as well as a voltage output to one side of each bridge amplifier. An RMS-to-DC converter was added to the amplifier current signal, which was input into an MADC for logging in the controls system. Additional power supply filtering was added to solve the problem of ripple on both +/-15V power supplies. The output of the kicker amplifiers were calibrated to determine the output current for each kicker setting in dB.

Several smaller pieces of the hardware were also altered for increased reliability. All spare diode boxes were modified to be identical, and the end connectors were changed to avoid the use of adaptors. The Khronhite filters and transformers were removed and replaced with passive low pass filters. Mechanical bracing was then added to support the diode boxes and filters. Bracing rods were also attached to the NCO daughter cards so they make a robust connection and do not flex. Front panels for the NCOs were machined and installed. Finally, the NCO outputs were connected to a VME 3123 digitizer to allow software to determine the phase of the NCO relative to the ADC sample buffer.

There are a myriad of interconnects in this system, and signal quality is only as good as the worst cable. Tests were performed with a network analyzer to check the integrity of the kicker cables going into the tunnel. Shortly after that, it was noticed that eight feedthroughs on the BBQ pickups needed to be repaired. Extra adaptors were eliminated where possible, and all interconnect points were wrench tightened. Several broken SMA “T”s were discovered, as well as four ¼” Heliax cables that needed to be re-terminated. Where appropriate, cables were re-routed to better paths and strain-relieved properly. New cable assemblies were made for the AFE-to-MADC paths as some cables were showing signs of wear.

### *Near-Integer Tune Modifications*

During RHIC Run-9, several Accelerator Physics Experiments (APEX) sessions were devoted to the investigation of near-integer betatron tunes as a possibility for future runs. The tunes were expected to be $Q_x$=0.88 and $Q_y$=0.97, yielding aliased sidebands of $f_x$=9.4kHz and $f_y$=2.3kHz. The filter characteristics of the AFE were such that the horizontal sideband would be in the passband (-3dB low frequency cutoff was about 8kHz), but the vertical sideband would be outside of the passband and therefore attenuated by approximately 20-30dB. Simulations were run using MATLAB to extend the passband and several AFE components were changed to lower the cutoff frequency to around 1kHz, see figure 1.

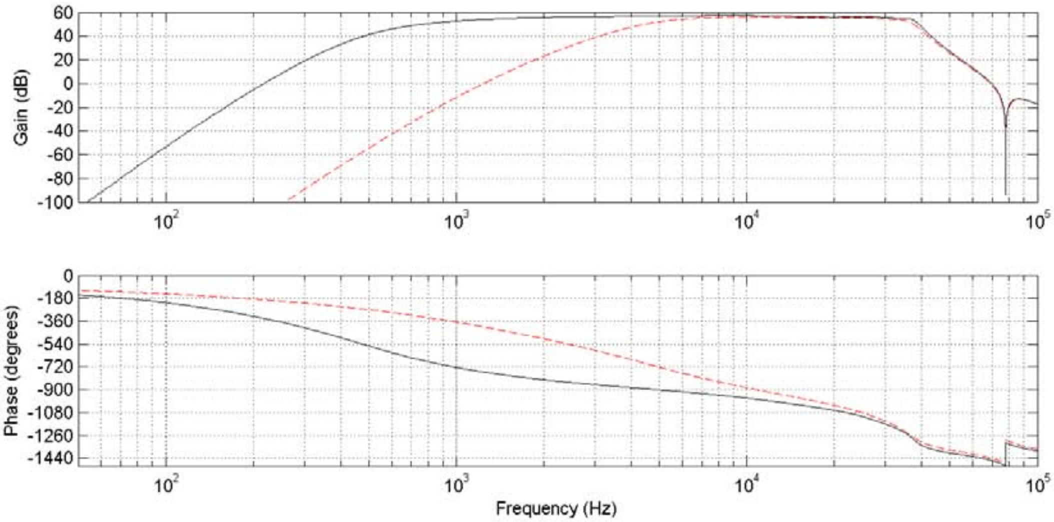

Figure 1: Frequency and phase response of the original (red dashed line) and modified (black solid line) AFE.

### *One-Third Tune Modifications*

Many APEX sessions during Run-10 were dedicated to the exploration of Q=1/3 tunes for use during future polarized proton operations. The VME 3123 digitizers that were installed had a maximum scan frequency of 100kHz. However, based on the revolution frequency and energies expected, tunes above 0.3197 and below 0.68 require scan frequencies greater than 100kHz. We were able to take advantage of the VME 3123 “channel doubling” mode to extend the sampling frequency to 200kHz by using two digitizer channels per signal. To use the channel doubling, a signal must be split and input to a channel pair: Channel 0 and 8, Channel 1 and 9, etc. Preliminary testing on the split-signal setup was done in the lab, and then first implemented in the blue ring, followed by the yellow ring. Minor software modifications needed to be made to correctly read the data from the digitizer. At around a tune of 0.42, the interrupt rate starts to oscillate, which is interpreted as reaching the limit of the CPU in the VME. Therefore, by using the channel doubling mode, we have extended the range of tunes that are possible to measure, and have a small deadband for tunes between 0.42 – 0.58.

## SOFTWARE MODIFICATIONS

### General Modifications for Operations

One of the main problems with tune feedback involved noisy tune data. The previous algorithm only used the last data point out of every sixteen data points. The code was changed to use the average of the last sixteen samples.

Various diagnostic parameters were added to the code, and the parameter which displays the number of interrupts processed per second revealed that not all scans were being processed. This was diagnosed as a competition for CPU time from another process. The other process would periodically corrupt beam transfer function data, was determined to be unnecessary, and therefore removed from the code.

Other changes include modifying the software to be more deterministic in the processing of data. Previously, if the code was not waiting to process data when new data arrived, the new data was never processed. A programming error was found and fixed in which digital filter parameters used for one application were overwriting those of another application. Also, precision phase optimisation and frequency-dependent phase correction were implemented.

The magnet control software for tune feedback was also improved. The code which is used to save feedback data for subsequent ramp replay was modified to save cached data to be immune to occasional delays in writing data to a file. Prior to this change, gaps and corruption of data would occur at the start of a ramp, presumably because of network slowdown at that time. The code was also modified to stop the control loop from delivering data to magnets when beam was lost from the machine. This change prevents the control loop from sending unphysical corrections to magnets which could ultimately result in a quench link interlock.

Two user-selectable digital filters labelled 40Hz and 20Hz were implemented in software, but their characteristics were not documented. Simulations were performed to determine their response; with a 25kHz input signal, the full width half max (FWHM) of the passbands of the output with no filter, 40Hz, and 20Hz filters were found to be 2310Hz, 820Hz, and 420Hz respectively. The BBQ system traditionally operates using the 20Hz filter, which is specified as a sequence of 11 taps and therefore its characteristics change in proportion to the scan frequency. This feature turned out to be beneficial for the near-integer operation because at lower frequencies, the filter passband becomes narrower. For example, at a scan frequency of 5kHz, the FWHM of the passband is 85Hz, which in turn reduces the interference of 60Hz harmonics.

### Near-Integer Tune Modifications

For near-integer tune operations, further modifications were necessary to the software for tune measurements and magnet control. In normal operations, the PID control algorithm had coefficients depending on the sampling frequency that scales with betatron frequency. The sampling frequency changed by a factor of ten at the near-integer tune. The PID loop was modified to use coefficients based on the given data rate such that the control becomes independent of the sampling frequency.

The dependence of the NCO phase on NCO frequency was previously defined in software as a hard-coded coefficient yielding linear dependence between NCO phase and the tune. This was changed to allow a user-specified linear coefficient instead.

The most critical and extensive modification for this mode of operation concerned the requirements for the magnet control code. In near-integer mode the data rate for sending tune corrections to the magnet power supplies were reduced by a factor of 10 or more, resulting in less frequent and larger requested changes. The amplitude of the requested correction often exceeded the capabilities of the power supplies. To resolve this issue, the magnet control code was modified to keep the setpoint generation rate above 180Hz.

### One-Third Tune Modifications

As mentioned in the corresponding hardware section, channel doubling of the digitizers was required for this operating mode. Therefore the software that handles the data acquisition needed to be modified to interleave the data coming from the digitzer. No other software modifications were necessary.

## RESULTS

During both Run-9 and Run-10, the BBQ system modifications and upgrades resulted in much success. Measurements were taken after most of the improvements had been implemented using frequency resonators to determine the resolution of the BBQ system. Using a linear fit between the vertical lines depicted in Figure 2, it was determined that the instrumental resolution was (1.9 +/- 0.1) x $10^{-6}$, or 0.05Hz. This measurement was also performed prior to many of the hardware and software changes, and the resolution at that time was calculated to be (4.3 +/- 0.2) x $10^{-6}$. Clearly the efforts to modify the system resulted in significant improvements to tune measurement resolution.

While 60Hz harmonics continue to be present on the signals, the BBQ system is now robust enough to “ignore” mains contributions and only lock on the correct tune value. Polarized proton operation at 100GeV includes a tune swing of approximately 0.05 during the ramp, which encompasses about 65 harmonics of 60Hz. Tune measurements and tune feedback worked successfully during these tune swings, with no user intervention.

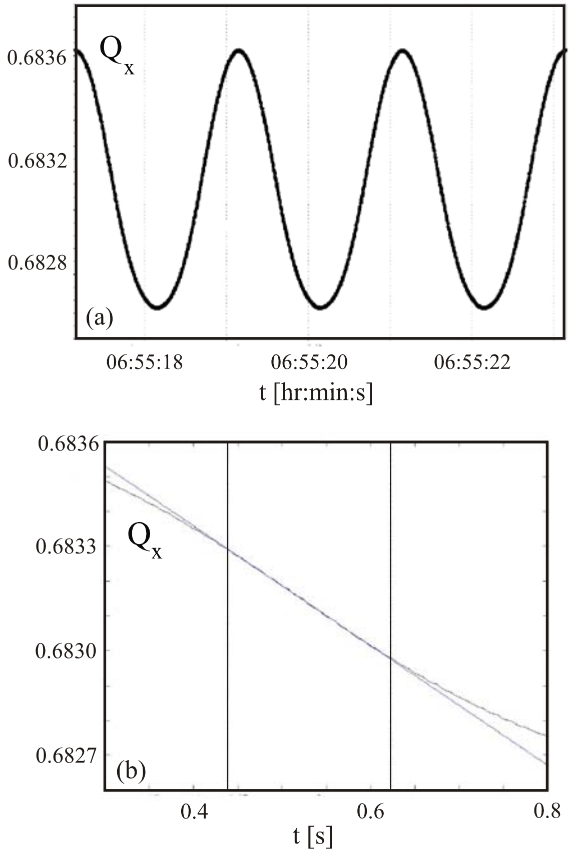

Figure 2: Measured tune in the blue ring with resonator input (a) with expanded axis scale showing linear fit (b) to determine resolution

Vibration of triplet quadrupoles in RHIC cause beam orbits to be perturbed at frequencies close to 10Hz [6]. Not long after establishing beam at full energies during Run-9, tune modulations at a 10Hz rate could be seen for the first time as seen in Figure 3. The oscillations between planes are observed to be out of phase thereby suggesting the modulation is not instrumental. Further comparisons between FFT signals from a BPM and BBQ indicate common dominant frequency contributions around 10Hz, see Figure 4 [5]. While the BBQ system was able to maintain a lock on the proper tune value, the 10Hz modulations were a limiting factor in resolution. For applications where precision tune measurements are required, digital filtering of the 10Hz modulations is implemented. Throughout Run-10, a 10Hz Global Orbit Feedback system is being tested in six RHIC locations in an effort to correct the 10Hz perturbations. Testing has gone well, and it is expected that the system will be fully deployed during the summer shutdown maintenance period.

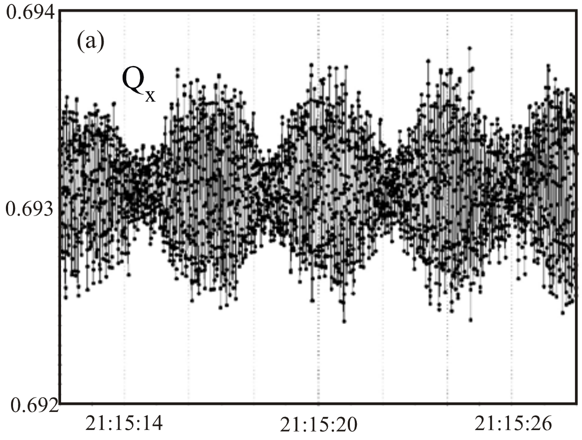

Figure 3: Horizontal tune data from blue ring at store during Run-9 with 10Hz modulation.

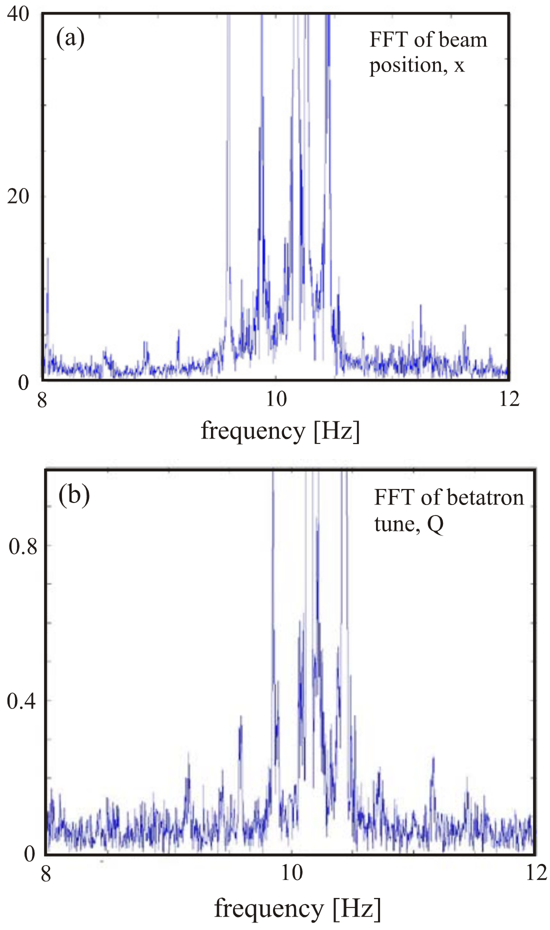

Figure 4: Fourier transforms of the horizontal beam position (a) and horizontal tune (b) showing similar frequency contributions from the ~10Hz perturbations

Whereas development time used to take many shifts over many days to ramp RHIC to desired top energies, development time during Run-9 took at most 6 hours to obtain proper tune feedback data for “replay”; see Table 1. (Replay is a setup that will reuse previously obtained tune feedback data to control magnet corrections during a ramp.) Prior to the upgrades, many ramps were lost as a result of the system losing a lock on the tunes. This changed during Run-9 as only one lost ramp could be attributed to the BBQ system, and that was because of a bad connector. No ramps were lost because of poor or no tune lock. The ramp failure rate decreased even further in Run-10 with only one failure attributed to BBQ as a result of improperly entered tune range scan values.

Table 1: Run-9 Ramp Development

| **Ramp Type** | **Commissioning Hrs. to First Replay Ramp** | **# Ramps to First Replay Ramp** |
|---|---|---|
| 250GeV<br>0.7m beta* | 6 (blue ring only)<br>5 (blue & yellow rings) | 12 |
| 100GeV<br>0.7m beta* | 3 (blue & yellow) | 4 |
| 100GeV<br>20m beta* | 3 (blue & yellow) | 5 |

After obtaining experience with both polarized proton and gold beams, and discovering that prior runs' observed ill-effects were no longer occurring, BBQ was no longer declared an "expert-only" system. Main Control Room Operations Staff were trained in a "classroom" as well as in a "hands-on, with beam" environment on how to use the system. Typically operations staff handle the day-to-day measurements, and experts are present during setup for different operating modes (i.e. APEX or energy change). Operators ran the tune and coupling feedback during Run-10 ramp development up through the physics handoff on December 31, 2009. Procedures and other reference documents are made available to operations staff at the Instrumentation Wiki site.

Coupling feedback is regularly used and has also seen improvements as a result of the hardware and software improvements. Prior to ramp development, the coupling of each beam is minimized at injection energy. If the measure of the coupling control is defined to be the rms of the signal strength in the orthogonal plane, it has been demonstrated that the precision on the decoupling control was reduced from +/-0.0414 during Run-8 to +/-0.0035 in Run-9 [5]. As with tune feedback, coupling feedback was automated and required no human intervention starting with Run-9.

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## REFERENCES

[1] M. Gasior, R. Jones, LHC Project Report 853.
[2] M. Gasior, R. Jones, "High Sensitivity Tune Measurement By Direct Diode Detection", DIPAC'05, Lyon, France, 2005, p. 312-314.
[3] R. Jones, P. Cameron, Y. Luo, "Towards a Robust Phase Locked Loop Tune Feedback System", DIPAC'05, Lyon, France, 2005, p. 298-300.
[4] P. Cameron, et al, "Progress in Tune, Coupling, and Chromaticity Measurement and Feedback During RHIC Run-7", PAC'07, Albuquerque, NM, 2007, p. 886-888.
[5] M. Minty, et al, "High Precision Tune and Coupling Measurements and Tune/Coupling Feedback in RHIC", BNL C-AD AP Note 366 (2010).
[6] C. Montag, et al, "Measurements of Mechanical Triplet Vibrations in RHIC", EPAC '02, Paris, France, 2002, p.1267-1269.