RHIC THIRD GENERATION PLL TUNE SYSTEM*

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Abstract

During the RHIC 2000 run a prototype PLL tune measurement system was implemented using commercial off-the-shelf hardware. To meet the requirements for tune feedback during RHIC 2001/2002, this system was migrated into RHIC BPM modules, whose flexible DSP/FPGA architecture permitted the specialized processing needed for tune tracking and feedback during acceleration, and whose existing firewire interface provided communication with the Control System. For RHIC 2003 this system has migrated yet again, to state-of-the-art DSPs in VME. We report here on various improvements, extending from the pickup through the analog electronics and digital processing into the Controls interface, and on the performance gains that resulted from these improvements.

SYSTEM OVERVIEW

Our approach to PLL tune measurement has been described in some detail in earlier papers[1,2]. Here the focus is on giving a brief overview of the present system, with some discussion of improvements, followed by a presentation of measurement results. Finally we discuss outstanding problems with this system and their possible solutions.

Description

A block diagram of the system is shown in figure 1. The system is driven by a 28MHz low-level RF signal piped in on heliax from the RF to the Instrumentation control rooms. This signal clocks a custom numerically controlled oscillator, which together with the Pentek DSPs sits in VME. All frequencies in the tune system are thus synchronous with the beam. The NCO output goes thru a chain of multipliers and dividers to provide the local oscillator for the mixers, the 455KHz IF, and the 4x455KHz I/Q demodulation clock for the digitizer. The mixers are suppressed carrier single sideband modulators. The 245MHz output on the excitation side is highpass filtered before entering a 10W class A amplifier, which drives the 25cm long 50 ohm kicker striplines through a difference hybrid and about 100m of heliax into the tunnel. During normal operation kicker power is typically in the milliwatt range. The kicker excitation travels with the beam through the betatron-tune-dependent phase shift between the kicker and the resonant pickup[3]. The output from the pickup is passed thru hi-Q cavity bandpass filters, boosted by 30dB, and again transported via 100m of heliax to the mixer, whose output is again at 455KHz. By including the betatron frequency in the local oscillator for up and down conversion, the tune signal is always at this 455KHz frequency and the need for a tracking filter at the input to the digitizer is eliminated. A 3KHz bandwidth ceramic filter removes the dominant difference signal at the revolution line before the 120dB variable gain amplifier chain that precedes the digitizer.

After digitizing the amplitude and phase streams of the I/Q demodulated data are low-pass decimated, first by 890Hz averaging filters, then by 40Hz IIR filters. The phase information is used by a PID algorithm to control the NCO frequency and track the tune. The amplitude

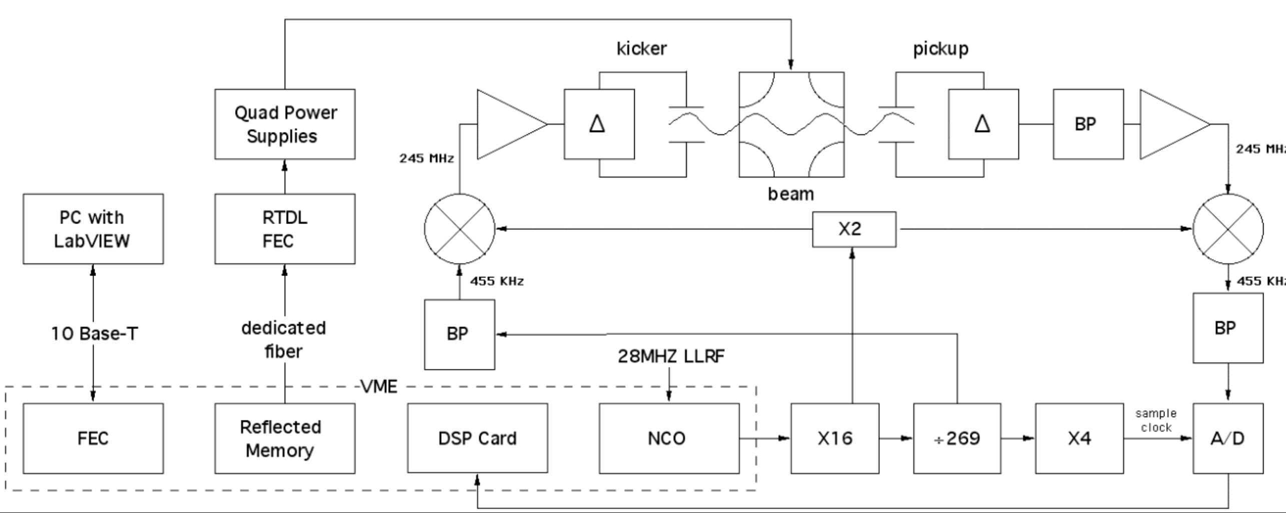

Figure 1 Block Diagram of the PLL/Tune Feedback System

information is used to adjust the kicker power, compensating for variations in the beam transfer function portion of the loop gain. Overall system control is accomplished via a LabVIEW user interface.

Improvements

Several improvements have been incorporated into the present tune measurement system:

- the kicker and pickup were moved to locations with larger beta, resulting in ~6dB of improvement in S/N
- the 1m long kicker was replaced with a 25cm long kicker, resulting in significantly improved beam excitation at 245MHz
- digitizer frequency has been increased, resulting in ~7dB of processing gain
- the 455KHz ceramic filter diminished amplifier saturation problems and increased the number of effective digitizer bits
- the 40Hz digital lowpass filter reduced noise bandwidth, giving ~20dB improvement in S/N
- horizontal and vertical planes were driven at different revolution line harmonics, diminishing the effects of coupling and tune crossing

With these improvements performance was significantly enhanced in comparison with the previously described system.

MEASUREMENT RESULTS

Tune Tracking during Ramping

Figure 2 shows data from a six bunch Deuteron acceleration ramp during the commissioning phase of the RHIC2003 run. The ramp starts at the left side of the figure. The right vertical scale is beam current, and applies to the trace that begins in the upper left corner of the figure. The left vertical scale is fractional tune. The continuous traces are PLL data, and the dots are kicked tune measurements. The tunes have large excursions and cross at transition, as a result of the beam being off center in the fast transition quadrupoles. Agreement between PLL and kicked tunes is reasonably good, although the kicked tune measurement often has difficulty in discriminating between horizontal and vertical planes, probably due to a combination of coupling and beta functions at the pickup. Coupling also introduces error in the PLL tune measurement due to spurious phase leaking from the opposite plane. There was a 1Hz 200µ radius modulation during this ramp to permit chromaticity measurement. The large width of the PLL line at various times during the ramp is from large chromaticity.

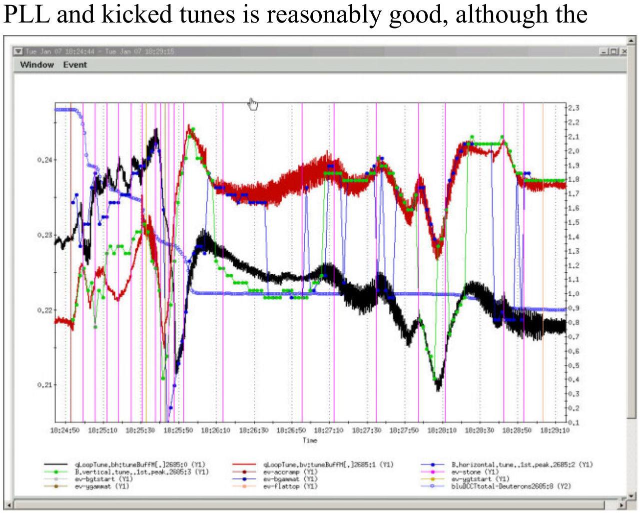

Fig. 2(color): Ramp Tunes

Tune Feedback

Figure 3 shows data from a six bunch Deuteron ramp with tune feedback[4]. Beam loss early in the ramp coincided with large tune fluctuation in the vertical plane, at a frequency of ~4Hz. Smaller fluctuations are visible late in the ramp in both planes, and in the horizontal plane after transition, and suggest that the tune feedback loop was close to the stability limit. Amplitude feedback on kicker power was not enabled for this ramp. Kicked tune data indicates that tunes were regulated at the level of .001 for a good portion of the ramp.

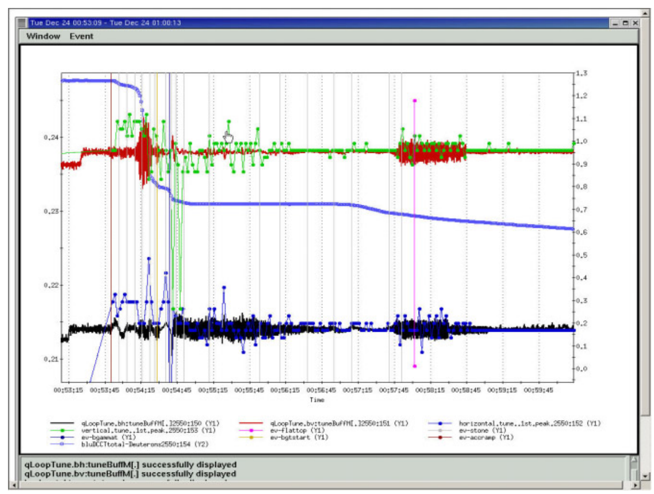

Fig. 3(color): Tune feedback

Figure 4 shows amplitude and phase data from the same ramp. The vertical scale is digitizer counts, which range between +/- 8192 with our 14 bit digitizers. The effects of transition and beam steering are clearly visible in this

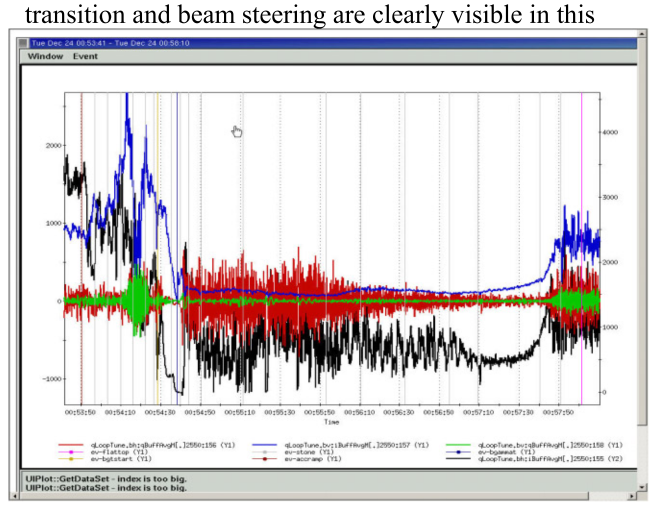

Fig. 4(color): Amplitude and Phase

figure, and will be discussed in more detail in the following section. It is interesting to note that shortly before transition the phase of the horizontal PLL jumped 180 degrees, and from that time on the loop would have been unstable if the gain approached unity.

Other Applications

The PLL has been employed in a variety of accelerator physics applications, including measurement and correction of non-linearities[5], chromaticity[6], and coupling[7], and measurement of beam-beam effects[8] and cryostat vibrations. A new technique[9] of coupling measurement was also investigated. Figure 5 shows data

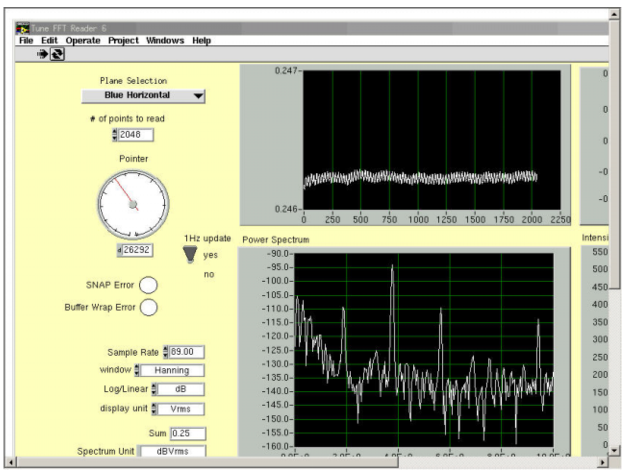

Fig. 5 Coupling Measurement

taken when two skew quad families were modulated at 2Hz and 180 degrees of relative phase. The upper right panel shows a brief time history of order 10^{-4} tune fluctuations. The lower right panel shows the FFT of the tune history. The energy at 4Hz appears as a result of coupling, and the amount of coupling can be calculated from the relative magnitudes of the 2Hz and 4Hz lines.

OUTSTANDING PROBLEMS

Preamp Saturation

Beam offset in the pickup drives the difference mode at the revolution harmonics, with amplitudes that can exceed the signal by ~60dB for offsets of a few mm. The problem is severe near transition, where bunch shortening extends the coherent spectrum of the 28MHz bunched beam up to the 245MHz pickup frequency, and where there are sudden large position and tune shifts due to firing of the transition quadrupoles. In addition, vertical IR bumps to minimize beam-beam effects during ramping are often not closed, and result in changing beam position at the PLL pickup. As the preamps saturate the noise floor comes up and the tune signal amplitude is diminished. These effects are visible in fig. 4 in both planes near transition, and in the vertical from transition to flattop. A servo on pickup position helps with slow position changes, but further measures are required for fast changes at transition. We continue to study methods of fast electronic compensation.

Coupling

While separating horizontal and vertical excitations in either or both time and frequency domains offers some relief, inevitably spurious phase from coupling comes through the beam, and can probably only be dealt with by minimizing coupling and maximizing tune separation.

Chromaticity Variations

Beam studies of the effect of chromaticity on PLL tune measurement were performed. Chromaticity was varied over a large range (from ~3 to ~19) while observing the effect on PLL amplitude and phase signals. The effect was surprisingly small, for reasons that are not yet understood. The conclusion has been that chromaticity control is probably not an issue for PLL operation.

Phase Compensation during Ramps

Several hundred meters of heliax carry 245MHz signals to and from the PLL pickups. During ramping the resulting phase shifts can be as great as ~700 degrees, and must be digitally compensated to within ~10 degrees. In theory this should be straightforward, but in practice anomalous phase shifts are observed and have not been understood. This causes phase compensation to be an often painful trail-and-error process. The planned solution is to move the mixers into the tunnel.

Emittance Growth

Measurable emittance growth results from kicker power of ~1W. At kicker powers below ~20mW there is no measurable emittance growth during ramping or store.

PID Loop Tuning

Loop gain is constrained by the fact that tune dither must be less than ~.001 to minimize beam loss during tune feedback, rendering typical PID tuning algorithms inapplicable. We are exploring alternative tuning algorithms, and alternatives to the PID control algorithm.

CONCLUSION

Tune feedback has been repeatedly demonstrated. Evolution to a true operational system continues.

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