Betatron "Ping" Tune Measurement System for the IUCF Cooler Synchrotron/Storage Ring*

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Abstract

A system has been developed for nearly real-time measurement of the coherent betatron fractional tune, ΔQ, in the IUCF cooler synchrotron/storage ring. This system measures the horizontal and vertical beam position on a turn-by-turn basis for beam currents in the range from $< 1\ \mu$A to > 1 mA. A fast Fourier transform of this position data is performed by a PC-based DSP module at a rate of 10 measurements per second yielding the betatron fractional tune. This tune information has been used to modify ramp parameters in order to minimize the tune shift. This paper describes the ping tune system's overall design principles, details of the various electronics systems, and compares the theoretical performance with the measured performance.

I. INTRODUCTION

The ping tune system, PTS, was developed in order to allow the operators to easily and quickly monitor and control the betatron tune[1]. The previous tune measurement method, rf knockout [2], works well for non-ramped beam; in this regime there is only a single tune to be measured and the machine cycle time can be made very short, $\ll 1$ s. During ramped beam operation, however, many measurements (as a function of time) must be made and the machine cycle time can be very long (> 10 s); in this regime rf knockout is excessively time-consuming.

A further advantage of the PTS is that it is nondestructive whereas rf knockout is destructive. The rf knockout system excites the beam with a transverse rf electric field; when the excitation frequency, f_{KO}, is equal to $\Delta Q \pm nf_0$ where n is an integer and f_0 is the revolution frequency, betatron oscillations with amplitudes exceeding the machine aperture can be excited. In practice, one varies f_{KO} until beam loss is observed. The PTS system, on the other hand excites small amplitude betatron oscillations which the electron cooling system can quickly damp.

The IUCF Cooler Synchrotron/Storage Ring is hexagonal with a circumference of 86.82 m. The relative

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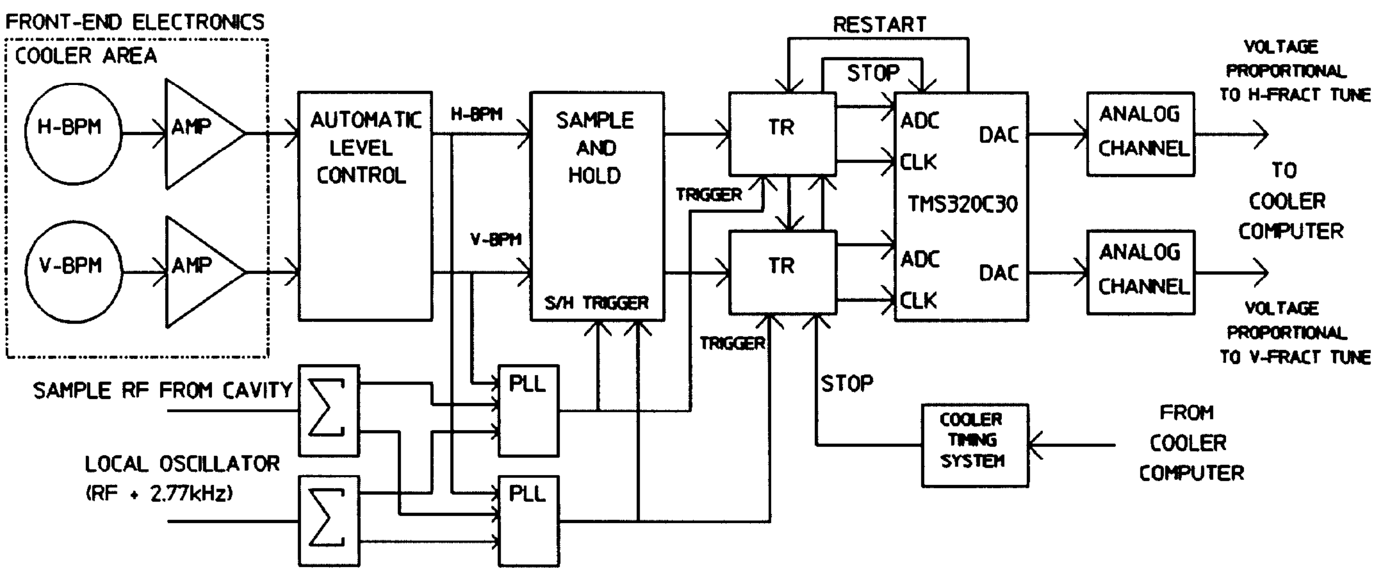

Figure 1. The ping-tune system is used to measure the betatron fractional tune of the IUCF cooler synchrotron/storage ring.

momentum spread of the beam is about $\pm$ 0.0001 FWHM. The rms normalized emittance of the electron-cooled proton beam can be much less than 0.1π μm. The beam lifetime can be as long as hours. A typical operation mode is stripping injection and cooling accumulation of 90 MeV H_2^+. The revolution period, T, for 45 MeV protons is 969 ns corresponding to an rf frequency of 1.03168 MHz. The typical full width at half maximum beam time spread, T_{FWHM}, ranges from 20 ns to 100 ns. Beam currents range from 0.1 to 1,000 μA. The bunching factor, BF, defined as the peak current divide by the average current, or $\approx T/T_{FWHM}$, can range from 1 for unbunched beam, to greater than 50 for highly bunched beams.

II. System description

The PTS consists of six major subsystems (Fig. 1): (1) the front-end electronics, (2) the automatic level control (ALC) with signal conditioning, (3) the sample and hold (S/H) module, (4) the phase-lock-loop (PLL), (5) the transient recorder (TR) and (6) the digital signal processor (DSP).

The front-end electronics consists of one horizontal and one vertical beam position monitor (BPM) electrode and amplifier [3]. The BPM electrodes are diagonally split cylinders. The electrode amplifiers produces two signals: one proportional to the beam linear charge density, and the other proportional to the product of the beam linear charge density and position relative to the center of the pickup. The first stage amplifier determines the system noise level; the electrode length, electrode and cable capacitance, and the intensity, velocity and BF of the beam determine the system signal level. We have evaluated both high input impedance field effect transistor (FET) buffer amplifiers and 50 Ω input bipolar junction transistors (BJT) amplifiers for this application. An FET input buffer amplifier was chosen as the first stage amplifier for this system because of the better low frequency response important for the relatively long ($\approx$ 40 ns) T_{FWHM} encountered most often in machine operations.

The dynamic operating range is extended through the use of a solid state ALC. The heart of this circuit is a CLC520 wideband amplifier [4] with voltage-controlled gain. The CLC520 has a 160 MHz small signal bandwidth, 0.5 degree linear phase deviation (to 60 MHz) and 0.04% signal nonlinearity at 4 V_{pp} output. The peak detected beam intensity signal is used as the feedback signal in a loop which maintains a constant output level with varying input levels. This same intensity feedback is also used to control the gain of the position signal. A dynamic range of over 55 dB has been obtained using this circuit, corresponding to a beam intensity variation of close to 10,000 since for electron-cooled space-charge-dominated beams, $BF \sim 1/I^{1/3}$ [5].

After the ALC, the short pulses (20 - 100 ns in length) are peak-detected by an active operational amplifier using a resistor in parallel with a capacitor (RC) in the feedback to stretch the pulse. Errors due to jitter and drift in the S/H timing signals are reduced by sampling this stretched pulse, rather than the very short unprocessed signals.

A CLC940 fast sampling, wideband track and hold amplifiers [4] is used to capture and hold both the intensity and position signals. This component has proven to be both reliable and easy to use. The CLC940 has a 150 MHz small signal bandwidth and a 12 ns track-to-hold time. The hold clock is derived from a rf cavity sample clock which has been locked in phase to the beam signal. This provides a reliable clock signal even with very low beam currents.

The PLL is necessary in order to track a single beam bunch as the beam energy, and consequently velocity and thus frequency, is changed. The changing frequency results in a phase shift due to non phase-matched cables. It is important to sample the BPM signal near its maximum amplitude during this energy ramping process. The PLL locks the trigger and beam signal by shifting the phase of the rf cavity sample clock in order to keep the relative phase near 90 degrees at all times. By locking the trigger circuitry in phase to the beam signals, no adjustments are required with varying beam velocity, bunching factor (the beam must be bunched) or intensity. This enables tune measurements to be made during the acceleration process where the beam velocity can change by over a factor of two.

The cooler ring revolution frequency can range from 1 to 2.5 MHz corresponding a beam energy ranging from 45 to 415 MeV. In order to digitize at these rates a high-speed TR is used. The DSP Technology Inc. 2012 TR [6] has 12 bit resolution, 8k memory, and can sample at rates up to 10 MHz. Once the TR buffer is full, the digitized data is replayed at a 100 kHz rate into a Spectrum TMS320C30 Real-Time System DSP board [7]. The DSP board performs a 1024 point fast fourier transform (FFT), which yields the tune information. A voltage proportional to the tune is than output by the DSP board. This information is displayed on the cooler control console as well as on a digital oscilloscope for observation during a cooler ramp cycle.

The DSP board resides in a personal computer (PC). All software changes can be made and complied on the PC. The C programming language is used along with a set of SPOX application programming interface (API) high-level functions [8]. Using the provided high-level functions, complex operations such as FFT's become trivial one line function calls. The DSP board is a user-friendly system requiring little development time.

At the heart of the DSP board is a Texas Instruments TMS320C30 processor [9] running at 33.33 MHz with 32-bit memory and I/O busses. Analog interfacing is accomplished via two 16-bit, 150 kHz analog-to-digital converters and two 16-bit, 1.5μs digital-to-analog converters.

III. System Operation and Performance

A. System Operation

A small coherent betatron oscillation is excited by a horizontal and/or vertical kicker magnet. A single measurement, or multiple measurements up to a rate of 10 measurements per second, can be made per ring cycle. The minimum measurement cycle time is limited by the 100 kHz transient recorder playback rate. A timing signal from the cooler computer controlled timing system initiates a measurement. This signal, via hardware logic, fires both kicker magnets and triggers the data acquisition system. The kick amplitude is set via the control console. The beam can be kicked in a single plane or in both planes at the same time. The beam loss due to the kick must be monitored. If the beam is kicked too hard, the beam current could fall below the data acquisition threshold level. If the beam is kicked too little the oscillation will be weak and the signal-to-noise ratio will be poor. A beam loss of approximately 1 dB seems to work very well for a single kick. An FFT of the first 1024 beam position points after the kick yields the fractional tune.

B. System Performance

A signal to rms noise voltage per channel ratio of 5 is necessary to ensure a 99.9% probability of detecting the correct tune. The signal voltage on one of the electrode pairs, V_S, is:

$$V_S = \frac{I\,BF\,L}{2\beta c\,C}\,\frac{x}{R}$$

where I is the beam current, L = 0.15 m is the electrode length, $\beta = v/c$ and c is the speed of light, $C \approx 60$ pF is the input capacitance, and $x/R \approx 0.05$ is the kick amplitude over the pickup radius. The total voltage noise is $\approx 25\ \mu$V due to the 4.6 nV/$\sqrt{}$Hz FET input voltage noise which is attenuated as $e^{-f/60\ \mathrm{MHz}}$ due to cable loss. This noise power is distributed equally in each of the 1024 channels (yielding 0.79 μV/channel). If the system noise were dominated by this white noise, then the tunes could be acquired with peak beam currents ($BF \bullet I$) as low as $\approx 6\ \mu$A. In this system, however, we have found that coherent rfi limits the system performance, though accurate measurements can be made with peak currents as low as 20 μA with x/R = 0.05.

Tune information has been obtained during an energy ramp cycle. A problem encountered during this measurement is beam current loss. A typical ramp time is 3 s, if the beam is kicked every 100 ms a substantial beam loss can occur since cooling does not occur during ramping. For this reason smaller kicks must be used when operating in this mode. At higher energies a larger kick is required to produce the same amplitude oscillation . Consequently, the tune is sometimes not acquired toward the end of the ramp. This problem can be avoided by measuring smaller time intervals of the overall ramp and adjusting the kicker amplitude accordingly.

V. Conclusions

The PTS information has been used to modify the tune during an energy ramp from 45 MeV to 350 MeV as shown in Fig. 2. Using this system, tune information during an energy ramp can be obtained in a matter of minutes compared to hours with the rf knockout method. This system will better enable operators to duplicate machine performance and operating characteristics from one run to another.

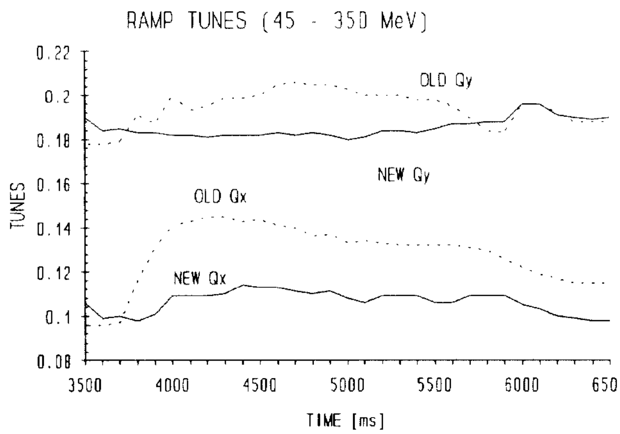

Figure (2). Reduction in tune variations during a ramp after 2 iterations.

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