Beam Diagnostic Systems in the IUCF Cooler and Cyclotron

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Abstract

Beam diagnostics for the IUCF Cooler synchrotron which have been recently developed include a beam phase feedback system to damp synchrotron oscillations induced by the rf system and a transverse phase space tracking system to measure the betatron fractional tunes and to investigate non-linear beam dynamics. New cyclotron diagnostic systems include a new beam timing system which has been improved in sensitivity by over a factor of 10, a cyclotron beam turns counting system, and an electrostatic quadropole magnet modulator to vary beam intensity in synchronization with the beam switching magnet. The design, performance, and problems associated with these systems are discussed.

I. Cooler Beam Diagnostics

A. Beam phase feedback

The cooler low level rf system uses a DDS (Direct Digital Synthesizer) with 512 Hz resolution for acceleration. These fairly large discreet steps, corresponding to a $\Delta p/p$ of about 0.006% (to be compared with the Cooler momentum acceptance of ± 0.2%) occur at rates comparable to synchrotron oscillation frequency, typically 2 - 5 kHz. Consequently large synchrotron oscillations are induced during acceleration. Although the effect of these steps can be reduced by lowering the phase-locked-loop (PL^2) bandwidth, if the bandwidth is made too small the loop cannot track the ramp without losing lock; in addition, as the loop bandwidth is decreased, additional noise from the VCO, which also heats the beam, is introduced. As a result, with an optimized PL^2 bandwidth, we typically lost about 60% of the beam during acceleration.

To solve this problem we built a beam phase feedback (BPF) system. The BPF system compares the phase of a signal from the rf cavity with a beam signal from a wall gap monitor. Because the rf system operates at many different harmonics of the fundamental revolution frequency it was necessary to include an adjustable phase shifter with discreet settings for each harmonic number in series with the beam feedback signal in order to maintain a 90° phase difference between the beam and cavity monitor signals for the ECL discriminator which operates with an I.F. of 10.7 MHz. The discriminated phase signal, after being processed by a computer-controlled filter with adjustable cutoff frequency and gain, is fed into the PL^2 upstream of the loop filter. The performance of this system is demonstrated in Figure 1, which shows the damping of a deliberately induced synchrotron oscillation as a function of the system closed loop gain.

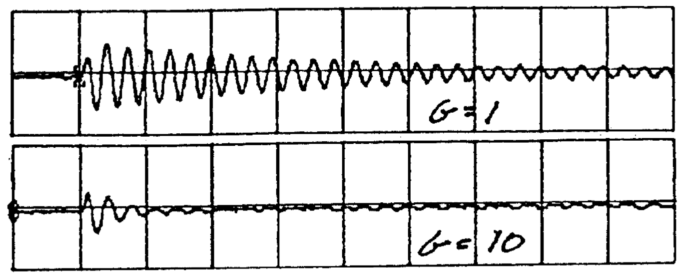

Figure 1. Beam phase with repect to the rf system as a function of time with the damping system in operation. Vertical: 45°/div; Horizontal: 1 ms/div. Top trace: BPF relative gain = 1; bottom trace: BPF relative gain = 10.

This system has increased transmission efficiencies during acceleration for about 30% to close 100% The beam lifetime is also greatly improved. The system dynamic range is 50 dB (from 1 μA to 300 μA) limited on the high end by the saturation level of the beam pickup amplifier (easily correctable) and on the low end by poor signal to noise.

The rf low level system also uses an HP-3325A synthesizer when operating at stationary frequencies. In this operating mode the phase error signal is fed into a phase-shifter with the same desirable effect.

B. Cooler beam phase space tracking system

1. System description

The extremely small emittance and momentum spread of the electron-cooled proton beams makes the Cooler an ideal laboratory for the study of nonlinear beam dynamics with unprecedented resolution. A data acquisition system is being developed to track the position of a single beam bunch in transverse phase space on a turn-by-turn basis in the Cooler. This system consists of four major subsystems: (1) the front-end electronics, (2) the level control with signal conditioning, (3) the sample and hold (S/H) module and (4) the digitizer.

The front-end electronics consists of two existing beam position monitor (BPM) electrodes separated by a betatron phase advance of close to 90°. The electrode amplifiers produce signals proportional to the beam intensity and the product of the beam position and intensity and have 55 dB gain.

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The automatic level control module increases the system dynamic range. The peak signal voltage is used in a feedback loop to adjust programmable step attenuators with 10 increments. After the attenuators, the short pulses (≈ 5 - 10 ns in length) are peak-detected by a passive circuit having a switch-selectable RC decay time which minimizes sampling errors due to jitter and drift in the sample and hold (S/H) timing signals.

The S/H module samples the peak-detected position and intensity levels with high speed sample and hold amplifiers having a 12 ns track-to-hold settling time. The output of two S/H modules are fed into a 2:1 analog multiplexer enabling a single digitizer to record both the position and intensity signals; the S/H electronics also reduce the required digitizer speed. Consequently, we have considerably reduced the system cost by minimizing the required speed and quantity of the digitizers. The trigger clock operates off the beam intensity signal and runs at the pulse repetition frequency divided by the rf harmonic number. The system can operate with beam fundamental revolution frequencies of up to 2.2 MHz.

We use a commercial transient recorder, DSP 2012, (TR) which has 12 bit resolution and an 8 k sample buffer as the digitizer. The TR is a CAMAC module which interfaces to the VAX network enabling the use of many existing software packages, consequently minimizing the amount of software overhead.

2. System operation and performance

The system is presently being developed for betatron fractional tune measurements and nonlinear beam dynamics studies. The beam is kicked using a horizontal kicker magnet. A fast fourier transform (FFT) of the beam position data after the kick yields the fractional tune as shown in Figure 2.

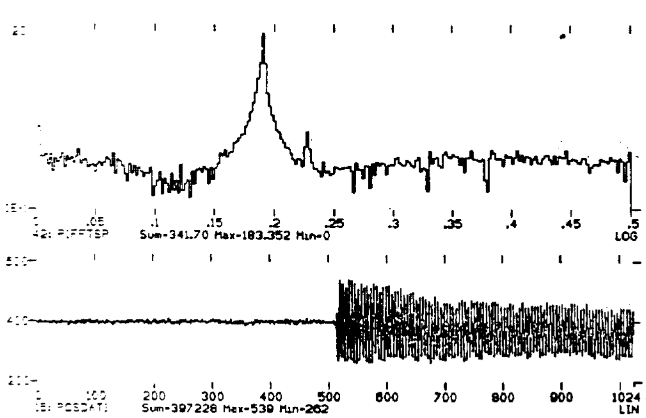

Figure 2. The bottom portion of the figure shows the beam position of a single beam bunch for 1024 turns. At turn 512 the injection kicker is fired producing a coherent betatron oscillation. The top portion is an FFT of the recorded beam postion; the peak corresponds to a betatron fractional tune of 0.189.

The system noise is determined by the input noise in the first amplifier (≈ 0.5 nV/√Hz) and the electrode sensitivity ($V/I_{peak}x_{mm}$) is about $0.2/\beta$ Ω/mm. Consequently, operating with peak currents (the product of current and bunching factor) of about 100 μA, a bandwidth of about 100 MHz, and a value for $\beta = v/c$ of 0.3, we expect rms noise of less than 0.1 mm. Although normalized beam position resolutions of 0.13 mm have been observed, more systematic testing is needed. The system has demonstrated a 1% amplitude linearity over the 10dB step attenuator range (Fig. 3).

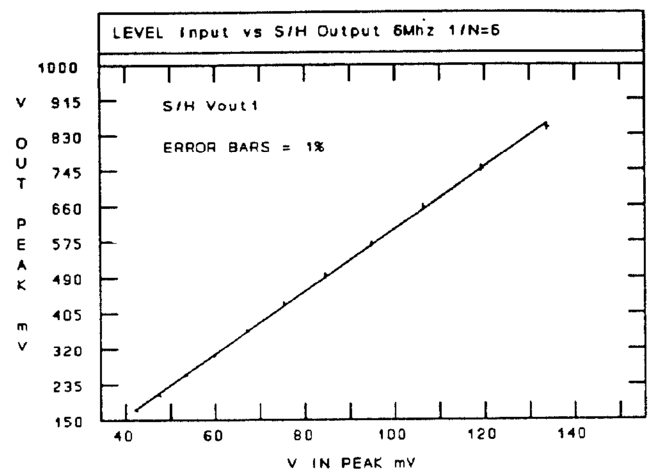

Figure 3. System linearity as a function of voltage in (x axis) vs voltage out (y axis). A simulated beam pulse input was increased in 1dB steps. The error bars are 1%.

Since the trigger circuitry operates directly off of the beam signals, no adjustments are required with varying beam velocity, harmonic number, bunching factor or intensity. This enables tune measurements to be made during the acceleration process, even where the beam velocity can change by over a factor of two.

Studies of the Poincaré (x,x') map, mapping of resonance islands boundaries and dynamical aperture studies using this system for data acquisition will begin this summer.

III. Cyclotron Beam Diagnostics

A. New beam timing system electronics[2]

The beam timing system provides an rf signal phase-locked (≈ ± 100 ps) to the beam from the cyclotron for experimentalists to use as a stop signal in energy measurements of reaction products using time of flight. Operation with the very low beam currents from the cyclotron (as low as a few nA) is very difficult and we have made many improvements in our system in order to operate with currents of this level. Formerly, the lowest intensity beams we were able to operate reliably was ≈ 25 nA. There were two principle problems: wideband noise (causing an unacceptable amount of jitter in the timing signal) and rfi (causing changes in the phase of the timing signal with changes in the beam current).

The wideband noise problem was eliminated by replacing the HP 8405A vector voltmeter, which was used as the system phase detector, with a modified BPM system low bandwidth detector (LBWD). This reduced the amount of wideband noise by about an order of magnitude, to the level expected given the system bandwidth and pickup amplifier noise figure.

The maximum permissible amount of coherent rfi at the pickup for satisfactory operation with beam currents of 1 nA is about 2 nV at the second harmonic of the cyclotron rf frequency, typically 60 MHz. Despite all efforts at rfi shielding, such rfi levels could not be obtained. Consequently, we decided to operate the system at a frequency which is a harmonic of the beam pulse repetition frequency but not a harmonic of the rf frequency by using pulse-selected beams. The beam is pulse selected $1{:}n$ using a prebuncher operating at a frequency of f_{cycl}/n where f_{cycl} is the cyclotron rf frequency and n is an integer. In this situation, there is a beam signal at all frequencies given by mf_{cycl}/n where m is an integer, but rfi only when m/n is also an integer. The system operates with $m/n = 3/2$ for even n, and at $m/n = 5/3$ for values of n which are a multiple of 3. By changing the local oscillator frequency to 3/2 or 5/3 the cyclotron rf frequency (depending on the pulse selection of the beam) + 2.777 kHz, and adding an amplifier in the feedback at low gains, we have locked onto beams with intensities as low as 1 nA.

B. Beam turn counter

This system modulates the beam current at a frequency of about 100 kHz and measures and compares the phase of the beam current modulation detected at pickups immediatly before and after the cyclotron. An HP4195A Network Analyzer is used to monitor this phase difference, operating on a modulation sideband of a high harmonic of the pulse-selected beam repetition frequency which is not also a harmonic of the cyclotron rf system frequency.

In a test of this system we modulated the beam current by modulating the phase of the prebuncher rf systems. For a number of reasons, this is not a suitable system for modulating the beam intensity and we are installing a new beam intensity modulation system.(see Fig. 4)

C. Beam intensity modulation system

By first limiting the acceptance of the 600 keV beamline with two sets of 4-jaw slits, we can modulate the beam intensity by a factor of about 50 without altering the beam transmission efficiency through the following series of accelerators by modulating the voltage of an electrostatic quadrupole. The electrostatic quadrupole voltage will be modulated using a home-built triode vacuum tube which is being tested. Besides being useful for future beam diagnostic systems, this system will be essential for future beam splitting operations, where two simultaneous users require substantially different currents.

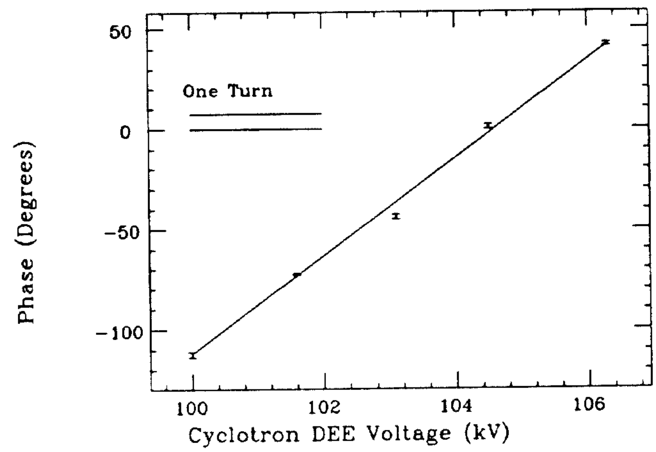

Figure 4. The cyclotron time space = n_{harm}/f_{cycl}. At the time of the test, f = 27.85 MHz, harmonic = 6, one turn = 215 ns and at 100 kHz modulation one turn = 7.75°. Because of the fractional tune, one of every 6 turns can be extracted.

IV. Conclusion

When a new beam diagnostic system is commissioned and used to make a systematic set of measurements, we invariably learn something new, if not exciting. Hopefully in the upcomming years we will have many interesting results to report on using these new systems.

V. Acknowledgements

We are grateful for the support of many staff members at IUCF especially Dave Caussyn, John Collins, Vladimir Derenchuk, Bill Jones, S. Y. Lee, and Terry Sloan.

IV. References

[1] Timothy JP Ellison, C. Michael Fox, Steven W. Koch, Liu Rui, "Nondestructive diagnostics for measuring the phase, position, and intensity of 15 enA beams from the IUCF cyclotron", *Proc. 11th Int. conf. on Cyclotrons and their Applications*, edited by M. Sekiguchi, Y. Yano, K. Hatanaka (Ionics, Tokyo, Japan, 1986) 279-283; Timothy JP Ellison, C. Michael Fox, Steven W. Koch, *"Noninterceptive wideband pickups for measuring the properties of very low intensity beams"* Nucl. Inst. Meth., B24/25 (1987) 873-876.

[2] Mark Ball, Timothy JP Ellison, and C. Michael Fox, *"New nondestructive beam diagnostics for the IUCF Cylotron and Cooler" Proc. of the 12th Int. Conf. on Cyclotrons and their Applications*, (Berlin, 8-12 May, 1989)