NEW NONDESTRUCTIVE BEAM DIAGNOSTICS FOR THE IUCF CYCLOTRON AND COOLER

Mark Ball, Timothy JP Ellison, and C. Michael Fox

The Indiana University Cyclotron Facility and Department of Physics
2401 Milo Sampson Lane, Bloomington, IN 47405 USA

ABSTRACT

New nondestructive cyclotron beam diagnostic systems which have been developed at IUCF include a beam time of flight system having a kinetic energy resolution of less than $\pm 5 \times 10^{-5}$, a buncher phase modulator which modulates the beam intensity at kHz rates and is an essential component in many new beam diagnostics we are developing, new beam current monitors capable of viewing this modulation, and improved electronics for our beam phase detector and beam position monitoring system. New Cooler nondestructive beam diagnostic systems include resonant pickups yielding a 23 dB S/N improvement over our wall gap monitors, a profile monitor with < 0.1 mm resolution, and a high bandwidth (300 kHz) beam position detector. New beam diagnostics under development include a cyclotron beam turn counter, a new extensive Beam Position Monitor system, and high voltage terminal bunchers. The design, performance, and problems associated with these systems are briefly discussed.

INTRODUCTION

This paper catalogues some of the work done with nondestructive beam diagnostics at IUCF since our report at the previous cyclotron conference. The report is limited to a description of the instrumentation; elsewhere, we have described some of the beam and accelerator properties that have been measured using these systems[2]. In the first section, we discuss diagnostics developed for the cyclotrons and cyclotron beam lines; in the second section we discuss diagnostics used in the Cooler.

I. CYCLOTRON BEAM DIAGNOSTICS

A. Buncher Phase Modulation

As reported previously[1], the IUCF cyclotron beams often contain a large amount of 60 Hz (line frequency) amplitude modulation. It was observed that the phase of this modulation could be shifted by ± 180° with respect to the line voltage by making very small changes in quiescent phase of various rf systems leading us to believe that by modulating the buncher phase at this same frequency it should be possible to eliminate this beam current amplitude modulation.

1. System description

To test this theory, we built a device which can modulate the buncher phase at 60 and 120 Hz. The amplitude of the phase modulation, and the phase of the modulation with respect to the line voltage are both adjustable. In addition, the phase modulator can also apply a square wave phase modulation of arbitrary amplitude in sync with an external TTL input.

In addition to the buncher phase modulator, we developed new current monitors which provide easy observation of the beam current modulation. The detectors operate with an IF frequency of 5.555 kHz and detect power from the beam at the second harmonic of the cyclotron rf frequency. Rather than rectifying and filtering the IF, we sample the IF output once per IF cycle using a sample and hold circuit which is followed by an adjustable filter (sampled output). This allows the system to have a bandwidth equal to that of the IF frequency without having a large amount of ripple at the IF frequency.

2. System operation

a. Beam current modulation reduction. Members of the beam dynamics group have used this system to decrease the amount of line frequency beam amplitude modulation and increase the beam current; however, the IUCF operations group have been reluctant to use this device in routine operations. One major drawback that we see now is that a small change in the quiescent buncher phase requires changing the phase of the modulation by 180°.

We have seen, however, that often the operators are able to substantially reduce the amount of beam current modulation by using the current monitor IF display as feedback in tuning the cyclotrons.

b. Beam splitting. The buncher phase modulator and beam current monitors have been essential for beam splitting operations[3]. We designed an audio frequency (< 10 kHz) magnet ($\int Bdl \approx \pm 30$ Gauss-m), powered by a commercial Kepco 20 V/20 A bipolar op amp supply, to rapidly switch beam back forth between two different users. The needs of the two users, however, might be quite different. For example, the Cooler may request the maximum possible amount of beam (e.g. 2 μA) for about 1 ms every ten seconds, whereas the other user may not be able to use greater than 100 nA for the other 99.99% of the time. By synchronizing the buncher phase modulator with this splitter magnet, the needs of both users can be simultaneously met (Fig. 1).

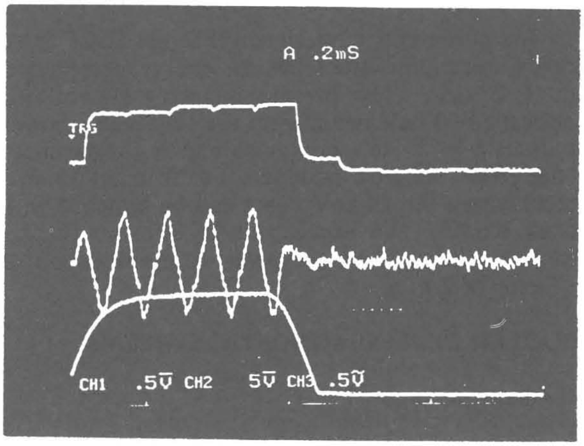


Figure 1. Beam current modulation using the buncher phase modulator. The lower trace is the splitter magnet waveform (200 μs/div). The center trace is the IF output of a current monitor *upstream* of the splitter magnet; thus upper most trace is the "sampled" output from the same beam current monitor. The beam current is being modulated from 300 to about 20 nA.

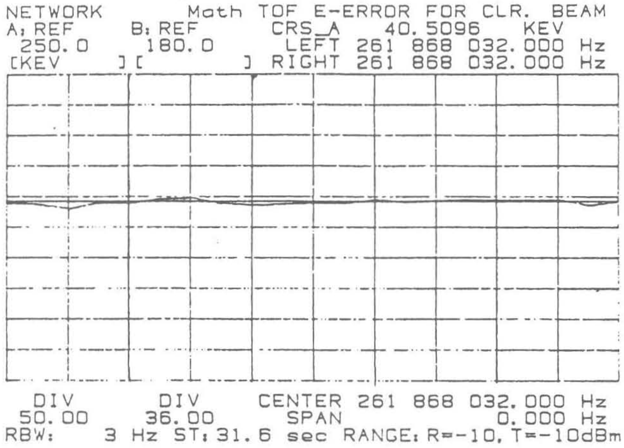
One infrequent drawback with this system occurs if the experimentalist is making energy measurements of reaction products using time-of-flight *and* if the beam is pulse selected, since the detuning of the beam by the buncher phase modulator interferes with the beam pulse selection.

c. Beam turn counter. A simple beam turn counter which is now under construction also makes use of the buncher phase modulators. In this case, the buncher phase modulator will be used to modulate the beam current at a 100 kHz rate. This current modulation is detected at two nondestructive current monitors--one before and one after the cyclotron, and the phase difference of this modulation is detected using a network analyzer. A single turn in the cyclotron nominally takes about 120 ns, or about 4° at 100 kHz--an easily detectable phase shift. This system is similar in principle with the system used at GANIL[4], except that we will deliberately modulate the beam with a single coherent frequency, rather than relying on the random beam current modulation frequencies already present.

d. Automatic rf system phase adjustment. The phase modulators can also be easily incorporated into a system which automatically optimizes the quiescent phase setting of various rf systems. Imagine that the phase of an rf system is modulated by a small amount from its quiescent setting. If the quiescent phase is too low, the beam current will increase as the phase is increased, and the beam current modulation will be in phase with the rf system phase modulation. Similarly, if the quiescent phase is too high, the beam current modulation will be 180° out of phase with the phase modulation. Thus, a simple feedback loop using the output of a phase detector as an error signal could be used to automatically keep the phases of all rf systems optimized for maximum transmission through the cyclotrons. To simultaneously tune many systems we will need to have separate systems operating on different frequencies, or multiplex a single system.

B. Beam time-of-flight (TOF) system

Two 7.5 cm length Q-electrodes, separated by 8.515 m, are mounted in a straight section of beam line immediately after the main cyclotron. This system, which is used with pulse-selected beams, measures the relative phase between the rf voltages induced by the beam on the two electrodes using a HP4195A network analyzer. The measurements are made at about 270 MHz at a harmonic of the beam pulse repetition frequency which is not also a harmonic of the cyclotron rf system frequency making the system absolutely free from rfi. A measurement with a ± 0.5° precision at this frequency (± 5 ps) gives an energy resolution of about ± 20 keV for a 100 MeV proton beam (a kinetic energy resolution of about $\pm 2 \times 10^{-4}$). In actual use, with high intensity beams (> 300 nA), we can resolve energy changes which are much smaller than this. The high precision of this system is shown in Fig 2, which is a copy of the network analyzer display which is made available to the operators.



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NETWORK          Math TOF E-ERROR FOR CLR. BEAM
A; REF      B; REF       CRS_A    40.5096    KEV
 250.0       180.0        LEFT 261 868 032.000 Hz
[KEV      ][          ] RIGHT 261 868 032.000 Hz

   DIV         DIV       CENTER 261 868 032.000 Hz
  50.00       36.00        SPAN            0.000 Hz
RBW:     3 Hz ST: 31.6 sec RANGE: R=-10, T=-10dBm
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Figure 2. Display for time of flight energy measurement for a 1.5 μA 108 MeV proton beam. The jagged line connects 20 separate measurements made at 1.5 second intervals. The straight line centered on the jagged line is the average value. The desired energy is at the vertically-centered horizontal graticule. The number printed in the upper right hand corner (40.5096 keV) is the average energy error. The vertical scale is 50 keV/div.

This system is now used as the standard for setting the beam energy for Cooler runs where the precise setting of the beam energy ($< \pm 2 \times 10^{-4}$) is essential. Besides being very precise and repeatable, the system is easy to use. For example, it is not necessary to precisely set slits and adjust the beam position and angle at the entrance and exit of an analyzing magnet in order for this system to give a valid measurement.

Although the precision of this system is quite high, there is an uncertainty of about 6×10^{-4} ($\Delta p/p$) in this system's accuracy. The system calibration was checked by measuring the energy mismatch of the cyclotron beam to the Cooler using Schottky signals and qualitatively looking at how the beam behaves as it is transferred bucket-to-bucket into the Cooler. Here we find that we must add about 52 ps delay as an error factor in order to provide the Cooler with an optimal energy 45 MeV beam. This corresponds to an error of about 54 keV (6×10^{-4} $\Delta p/p$). This may be due to an error in measuring the distance between pickups, the electronic delays in the system, or an error in our knowledge of the actual Cooler circumference by about 5 cm (5×10^{-4}). (We have observed that the Cooler circumference can be changed by an amount on this order by making certain changes in the closed orbit). Further comparison of the beam energy as measured by the TOF system and by matching to the Cooler for beams of different energies (and thus velocities) will tell us whether this error is an electronic error, or an error in either the distance between pickups or Cooler circumference. Another system with a much longer flight path may be installed in the beamline to the spectrometer. If installed, this system should be able to tell us what the actual Cooler circumference is.

C. New beam phase meter electronics

A new set of electronics has been designed for the beam phase meter[1]. The HP 8405A Vector Voltmeter which was used as the phase detector, has over 5 times the noise (white) to signal ratio that one would expect in a given bandwidth due to the signal to noise ratio of the input signal. This poor signal-to-noise ratio prevented the system from working reliably for beam currents less than 20 nA. The Vector Voltmeter was replaced by a modified beam position detector[1]. By merely bypassing the amplitude-to-phase conversion portion of the circuitry, we have a synchronous phase detector having a signal to noise ratio which is over 5 times greater than that obtainable with the HP Vector Voltmeter. This allows the system to lock onto beams with intensities as low as about 4 nA.

The coherent rfi at the second harmonic of the cyclotron rf, which varies from the equivalent of 0.2 to 2 nA depending upon the rf frequency, is now our major problem. We are going to make a small effort at reducing this rfi by another order of magnitude. If these efforts are unsuccessful, we have a number of ideas for electronic circuitry which we can install fairly easily in order to compensate for this rfi.

D. New beam position monitoring (BPM) system

We have developed a new simplified beam position electrode amplifier which increases the signal to incoherent-noise ratio by 6 dB with respect to our pervious design. The previous design was optimized for the Cooler frequency range of 1 to 20 MHz and used high input impedance FET buffers to give a flat response over this range. The frequency range used by the cyclotron BPM system, however, is from about 40 to 50 MHz (the 3/2 harmonic of the cyclotron rf system, and the third harmonic of the beam which is pulse selected 1:2). By using 50 Ω input impedance amplifiers the signal is reduced by about a factor of two (since the low frequency cutoff is about 90 MHz), but the incoherent noise voltage is reduced by about a factor of 5, from approximately 3.5 to 0.75 nV/√Hz. We are now in the process of producing 50 units (as was previously done for the Cooler) to instrument the beamline from the cyclotron to the K-600 spectrometer.

E. Terminal bunching system

Measurements have shown that the IUCF injector cyclotron injection system has an energy acceptance of about ± 2 keV. The present bunching system (which bunches the 600 keV beam from the terminals), however, puts about a ± 20 keV energy spread in the beam. We are therefore building bunchers for installation in the terminal where the 20 keV beam can be bunched with as little as 100 V. We expect this to improve the beam transmission through the cyclotrons (presently about 2%) by a factor of 2 to 5.

II. COOLER BEAM DIAGNOSTIC SYSTEMS

A. Resonant pickups

A number of 1/4 wavelength stripline resonant pickups were built to look at the very small Schottky signals in the Cooler. These pickups have a shunt impedance of about 10 kΩ; however, since the signal must be transformer coupled out (we use a very small, ≈ 4 pF, series capacitor to couple into 50 Ω system, electrically equivalent to a transformer), the effective impedance is only about 700 Ω ($= (50\Omega \times 10\text{k}\Omega)^{1/2}$). The pickups are varactor (voltage controlled capacitor) tuned, allowing us to adjust the resonant frequency by ± 5 MHz about the nominal resonant frequency of 45 MHz.

By using such a resonant pickup in place of the wall gap monitors in the beam phase meter, we could lower its useful range to about 0.3 nA, neglecting rfi problems. The pickup could be kept in tune by exciting it with a small signal at a higher harmonic, and using the phase between the source and the pickup response as an error signal to prevent phase errors due to drifts in the pickup's resonant frequency.

B. High bandwidth beam position detector

Besides the low bandwidth beam position detector[1], we have also built a high bandwidth position detector. This detector uses a 21.4 MHz IF, and has a maximum measurement bandwidth of 300 kHz. ECL discriminators and logic are used for signal leveling and phase detection. This system has a useful dynamic range of about 50 dB, but, due to the large IF bandwidth (600 kHz), the beam current must exceed a few μA before there is sufficient signal to noise for this system to operate.

C. Profile monitor

The stored ion beam transverse profile in the Cooler is measured by sweeping the proton beam through a 7 μm diameter carbon fiber and measuring the secondary emission current. The fiber is located in a region of high dispersion (4 m), so that the beam energy and transverse position are highly correlated. The sweeping is accomplished by frequency modulating the Cooler rf system, and thus the beam energy. With typical parameters we use, the beam moves transversely at a rate of about 20 m/s.

The secondary emission current is measured using a unity gain noninverting FET op amp (AD 515) with an input impedance of 0.5 MΩ. The signal to noise ratio is determined by the input impedance since we are operating in the regime where the noise is determined by the input voltage noise rather than the input current noise. However, the input impedance also determines the system bandwidth (about 27 kHz) due to the 12 pf capacitance of the fiber, feedthrough, and amplifier assembly.

This system is nondestructive in the sense that only a few percent of the beam is lost in traversing the fiber; on the other hand, since the present low level rf system we use can make very rapid rates of frequency change only if very large net frequency changes are made, after the measurement the beam is destroyed as it is accelerated out of the machine acceptance. In the future we may upgrade the low level rf to make it possible to move the beam through the fiber once adiabatically and stop within the cooler momentum acceptance.

An example of a measurement using this technique is shown in Fig. 3. Due to the fact that this measurement takes place in a region with both nonzero beta and dispersion functions, the beam size at this location is due to both the beam transverse emittance and longitudinal energy spread. The profile in Fig. 3 corresponds to a 45 MeV proton beam with a transverse emittance (one standard deviation) of less than 0.02 $\pi\mu$m (a 0.2 eV/k transverse temperature in the electron region), or an energy spread (FWHM) of less than 6 keV. Independent measurements show that although the electron-cooled coasting proton beam generally has an energy spread of about 2 keV, electron-cooled rf bunched beams have energy spreads of about 6 keV. Thus this system, as configured, is only able to yield an upper limit of the cooled beam transverse emittance. In order to obtain a lower limit on the cooled beam emittance, the fiber may be moved to a position in the ring which has the same dispersion function, but a larger beta function. In addition, we are considering methods of moving the beam across the fiber without rf: for example by using a set of bumper magnets to produce a transient local closed orbit distortion, or by accelerating the unbunched beam using our large 0.6 V-s capacity Faraday induction device (single turn transformer).

D. BPM LOG-I

The only way we have of monitoring the beam during a ramp is by using the intensity and position outputs of the BPM low bandwidth detector(LBWD). The intensity output of the LBWD is linear, so in order to improve the visual dynamic range of the signal, we convert this output to a logarithmic signal, (Figure 4).

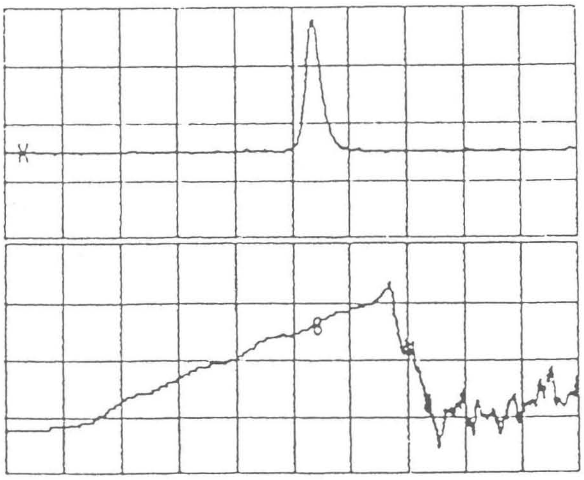

Figure 3. Cooler beam profile measurement (100 μs/div.). The upper trace is the secondary emission current (beam profile) from the 7 μm carbon fiber as an electron-cooled 45 MeV proton beam is swept across it (≈ 1.2 mm/div). The lower trace shows the beam position as measured by the high bandwidth beam position detector (≈ 2.88 mm/div). Synchrotron oscillations are evident due to nonadiabatic acceleration of the proton beam.

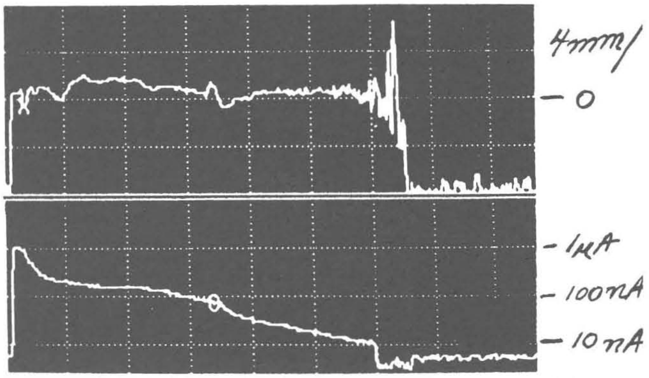

Figure 4. Cooler beam during ramp(500 ms.).The upper trace is position of beam from the LBWD. The lower trace is intensity of beam from BPM LOG-I. The traces show a 45 MEV proton beam ramped to 148 MEV. (0.2 s/div)

CONCLUSION

At IUCF we have developed a large amount of expertise in designing and building high precision beam diagnostics and there are many more interesting projects on the horizon. However, in the future, the Beam Dynamics Group at IUCF is going to place more emphasis *using* our diagnostics for analyzing and improving the performance of the accelerators. In addition, we are going to interface our diagnostics much more thoroughly to the controls computer and work on developing software to automatically make and analyze measurements, and improve the accelerator system performance.

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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. *The Indiana University Cyclotron Facility Scientific and Technical Report, January 1987 - April 1988*, edited by E. J. Stephenson. See sections on beam diagnostics and Cooler commissioning.

3. Dennis L. Friesel, Timothy JP Ellison, Terry S. Sloan, and Mark Ball, "Multiple beam operations at IUCF", these proceedings.

4. F. Loyer, "On line beam diaganostics at Ganil", *Proc. 11th Int. Conf. on Cyclotrons and their Applications*", edited by M. Sekiguchi, Y. Yano, K. Hatanaka (Ionics, Tokyo, Japan, 1986) 449-452.